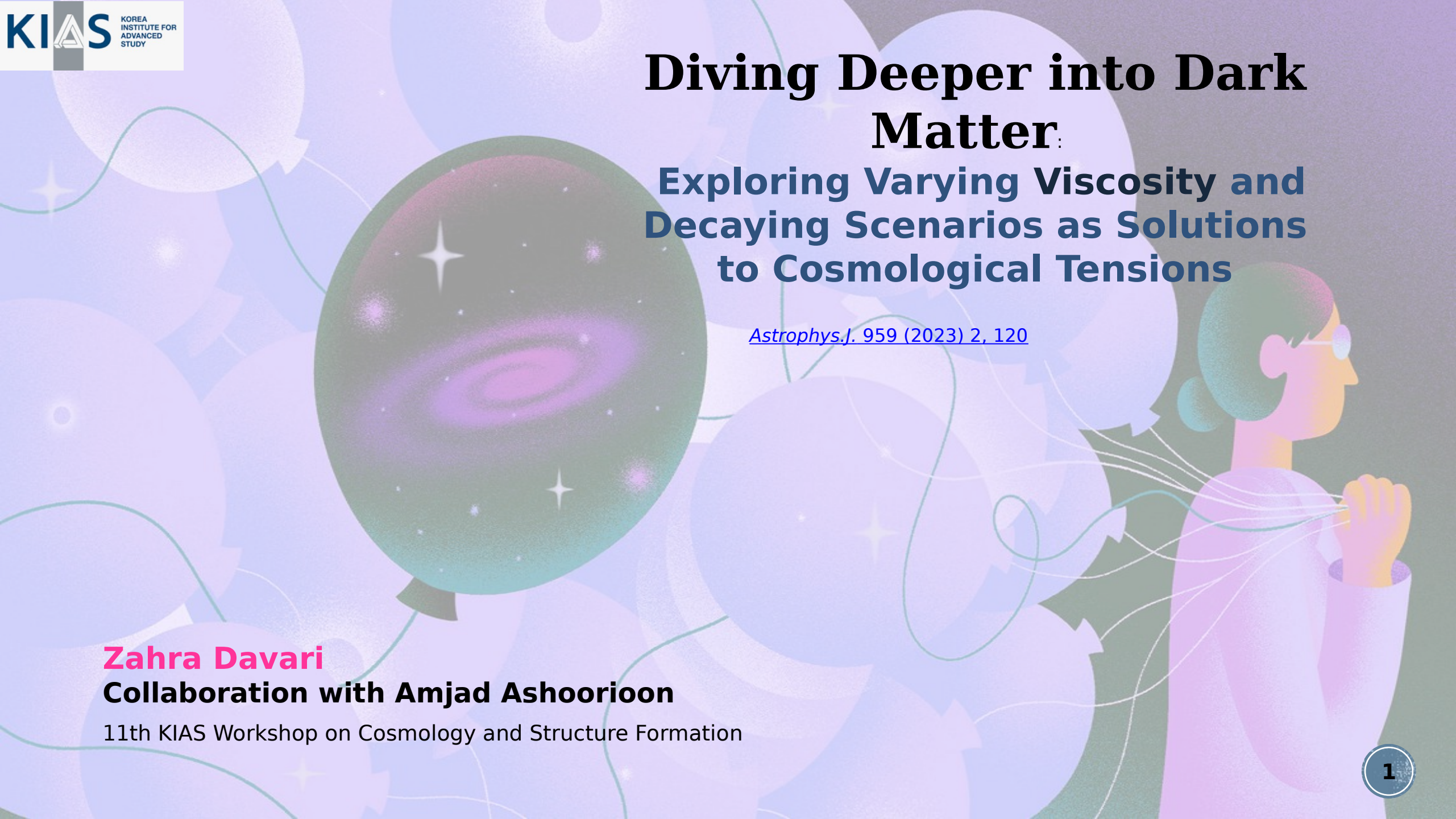
Diving Deeper into Dark Matter:

Exploring Varying Viscosity and Decaying Scenarios as Solutions to Cosmological Tensions

Astrophys.J. 959 (2023) 2, 120



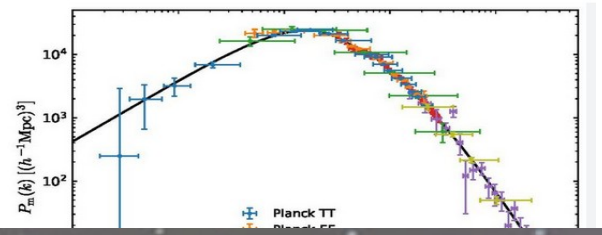
Zahra Davari

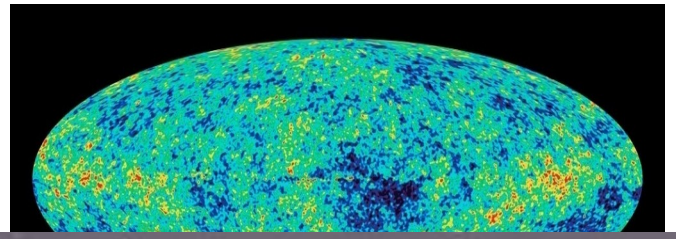
Collaboration with Amjad Ashoorioon

11th KIAS Workshop on Cosmology and Structure Formation

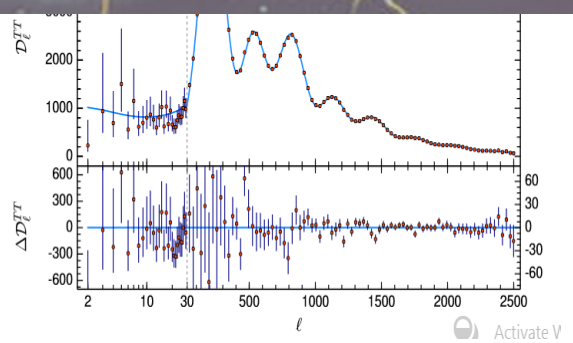
The Standard Model(ΛCDM)

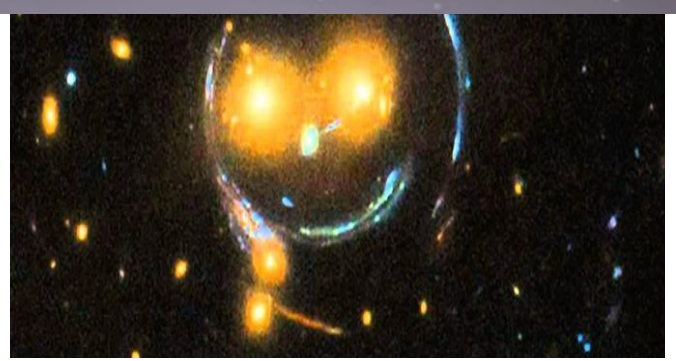












https://www.cosmos.esa.int

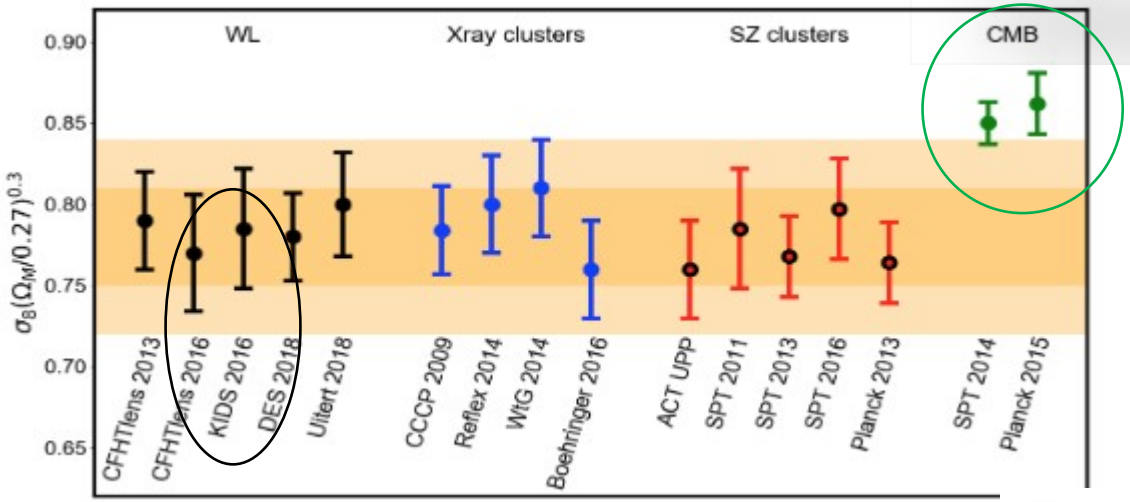
https://map.gsfc.nasa.gov/media/121238/index.html

https://science.nasa.gov/universe/galaxies/large-scale-structures

S_8 Tension

$S_8 = 0.834 \pm 0.016$

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

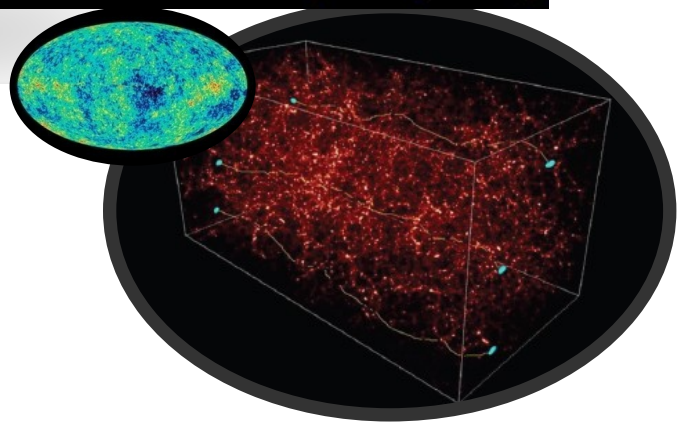


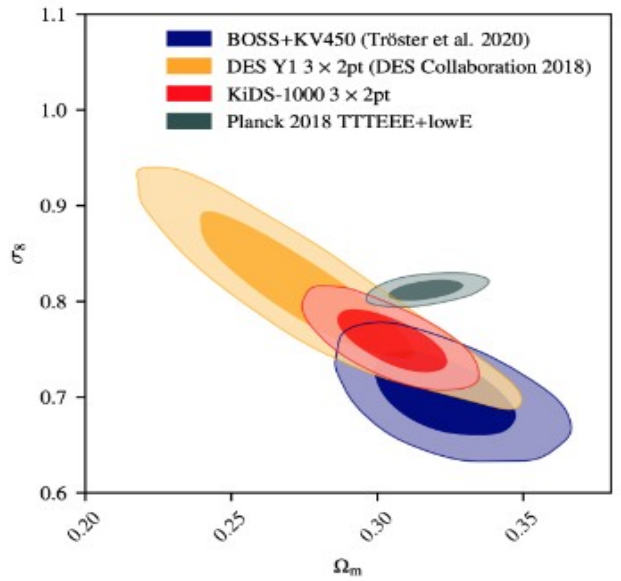


Planck and KiDS-1000.

$S_8 = 0.766^{+0.020}_{-0.014}$

KiDS-1000, Heymans et al., arXiv:2007.15632 [astro-ph.CO]





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Finding the reason for these apparent discrepancies has become the main driver of cosmological research.



The three unknown ingredients are:
inflation, dark matter (DM), and dark energy (DE).
In ΛCDM, inflation is given by a single, slow-rolling scalar field;
DM is assumed to interact only through gravity,
be cold and pressureless, and lack direct evidence of its existence;
DE is represented by the cosmological constant term Λ,
without any strong physical explanation.

What we already know about DM in the standard model of cosmology ΛCDM is that it is responsible for about 85% of the universe matter content and is a non-luminous, dark component of matter which must be non-relativistic or cold , massive and collisionless

Can alternative models of cold dark matter reduce cosmic tensions?



Viscosity in the cold dark matter can be caused in two different ways:

- Fundamental viscosity: This type of viscosity is generated due to the self-interaction between the dark matter particles.
- Effective viscosity: This kind of viscosity is expected to be generated on large scales as the integrated effect of the back-reaction of small scales non-linearities.

We write the energy momentum tensor for non-ideal CDM fluid

perfect flui $\tilde{T}^{\mu\nu} = (\rho + p)u^\mu u^\nu + p g^{\mu\nu}$

$$T^{\mu\nu} = \tilde{T}^{\mu\nu} + \Delta T^{\mu\nu}$$

bulk stress shear stress

$$\Delta T^{ij} = \Pi_B \Delta^{ij} + \Pi^{ij},$$

$$\Delta T^{i0} = \kappa \left[\Delta^{i\alpha} \nabla_\alpha T + T \frac{\partial u_i}{\partial t} \right],$$

$$\Delta T^{00} = 0,$$

$$\Pi_B = -\xi \nabla_i u^i,$$

$$\Pi^{ij} = -2\eta \left[\frac{1}{2} (\Delta^{i\alpha} \nabla_\alpha u^j + \Delta^{j\alpha} \nabla_\alpha u^i) - \frac{1}{3} \Delta^{ij} (\nabla_\alpha u^\alpha) \right]$$

Only bulk viscosity is a unique process that is allowed to occur on an expansive, homogeneous, and isotropic background

Weinberg, S. 1971, ApJ, 168, 175

$$u^{\gamma}_{;\gamma} = \frac{1}{\sqrt{-g}}\partial_\gamma(\sqrt{-g}u^\gamma) = \frac{1}{\sqrt{-g}}\partial_\gamma(\sqrt{-g})u^\gamma + \partial_\gamma u^\gamma,$$

$$\sqrt{-g} = r^2\sin^2\theta a^3(t),$$

$$(\partial_\gamma(\sqrt{-g})u^\gamma = (\partial_0\sqrt{-g})u^0 = 3r^2\sin^2\theta a^2(t)\dot{a}(t),$$

$$\frac{1}{\sqrt{-g}}\partial_0(\sqrt{-g}) = 3\frac{\dot{a}(t)}{a(t)} = 3H,$$

The bulk viscosity modifies the effective pr $p_{\rm eff} = p - 3H\xi$ as

$$\dot{\rho}_r + 4H\rho_r = 0 \Longrightarrow \rho_r = \rho_{r0}a^{-4},$$
$$\dot{\rho}_b + 3H\rho_b = 0 \Longrightarrow \rho_b = \rho_{b0}a^{-3},$$
$$\dot{\rho}_{\rm vdm} + 3H(\rho_{\rm vdm} - 3H\xi) = 0,$$
$$\dot{\rho}_\Lambda = 0 \Longrightarrow \rho_\Lambda = \rho_{\Lambda 0}.$$

$\xi(\rho_{\rm vdm}, H, \rho_{\rm vdm}H)$

- **M1**: Constant Anand, S., Chaubal, P., Mazumdar, A., & Mohanty, S. 2017, JCAP, 11, 005
- **M2**:proportional to the powers of the energy density $\left(\frac{\rho_{\rm vdm}}{\rho_{\rm vdm,0}}\right)^n$
- **M3**:proportional to the powers of the Hubble parame $\left(\frac{H}{H_0}\right)^m$
- **M4**: proportional to $\left(\frac{\rho_{\rm vdm}}{\rho_{\rm vdm,0}}\right)^n \left(\frac{H}{H_0}\right)^m$

$$\dot{\delta} = -3\mathcal{H}(c_s^2 - w)\delta - (1+w)(\theta + \frac{\dot{h}}{2}),$$

$$\dot{\theta} = -\mathcal{H}(1 - 3c_{ad}^2)\theta + \frac{c_s^2}{1+w}k^2\delta - \nu k^2\theta,$$

$$w = \frac{-3\xi(\rho_{\rm vdm}, \mathcal{H}, \rho_{\rm vdm}\mathcal{H})\mathcal{H}}{a\rho_{\rm vdm}},$$

$$c_s^2 = \frac{-\xi(m+1)\theta}{a\rho_{\rm vdm}\delta} - \frac{3\xi n\mathcal{H}}{a\rho_{\rm vdm}},$$

$$c_{\rm ad}^2 = -\frac{3\xi n\mathcal{H}}{a\rho_{\rm vdm}} - \frac{3\xi(1+m)(\dot{\mathcal{H}} - \mathcal{H}^2)}{a^2\dot{\rho}_{\rm vdm}}.$$

Anand, S., Chaubal, P., Mazumdar, A., & Mohanty, S. 2017, JCAP, 11, 005

Blas, D., Floerchinger, S., Garny, M., Tetradis, N., & Wiedemann, U. A. 2015, JCAP, 11, 049



CLASS

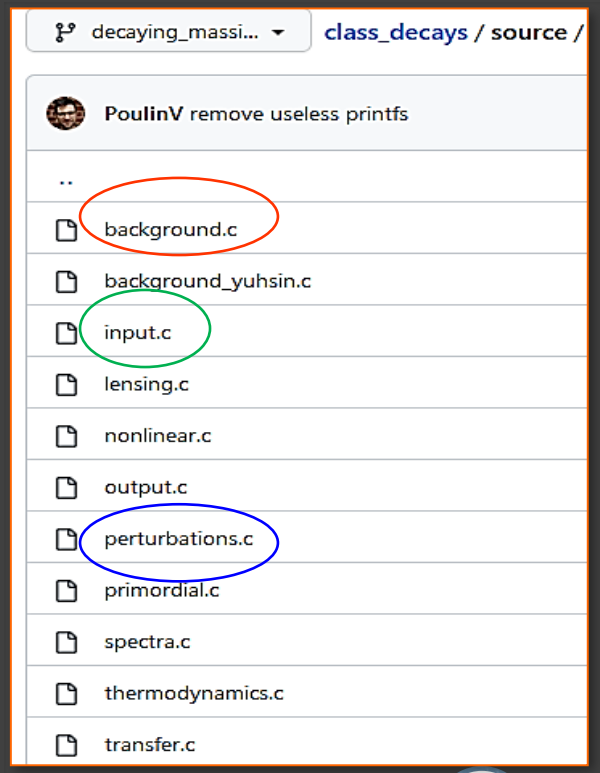
the Cosmic Linear Anisotropy Solving System



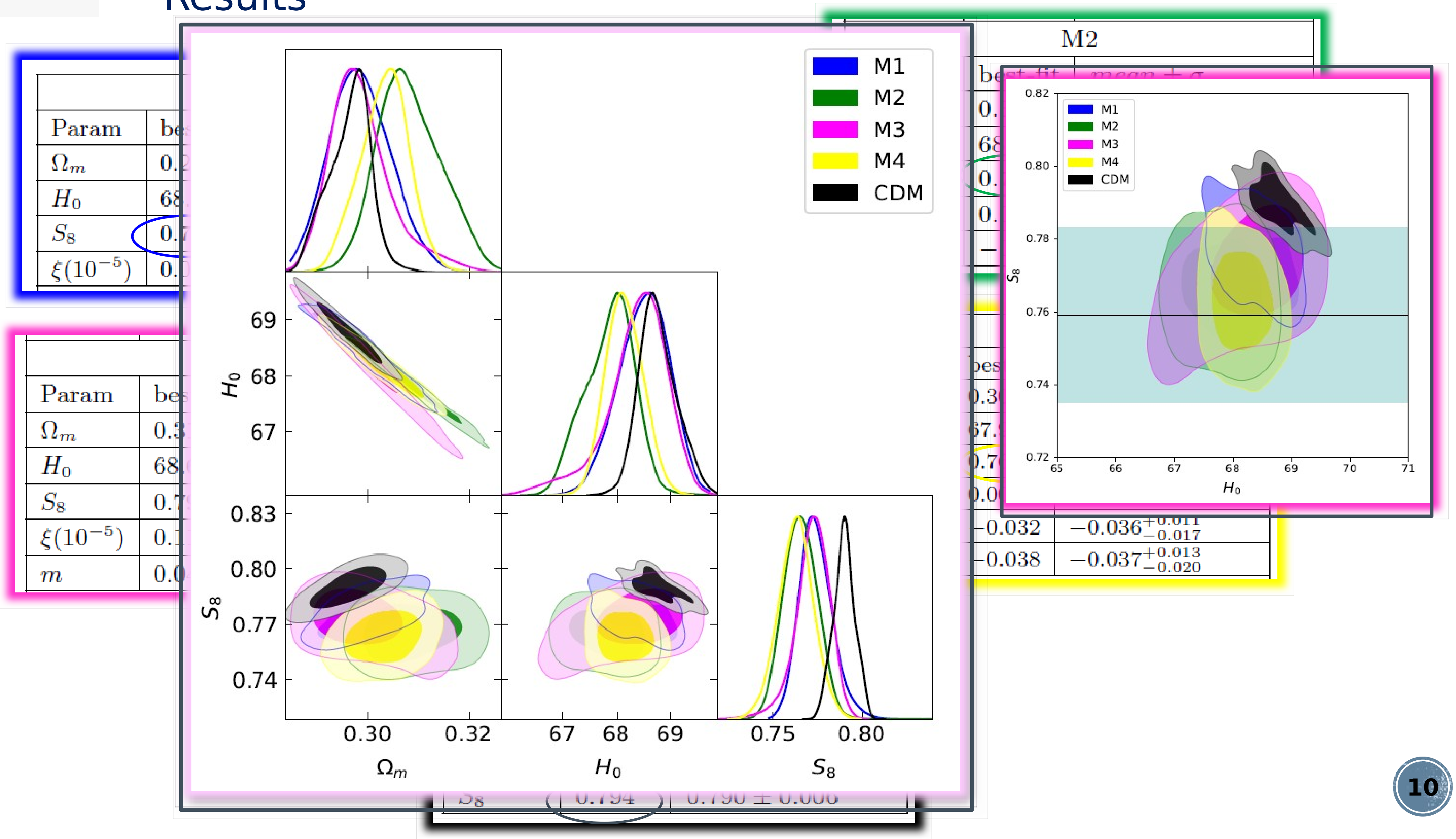
https://github.com/PoulinV/class_majoron
https://github.com/baudren/montepython_public

We modify the public Boltzmann solver **CLASS** for each type of dissipative mechanisms in the dark matter to calculate the cosmological evolution and CMB anisotropies. We perform the Markov chain Monte Carlo (MCMC) scans by **MONTEPYTHON-v3** with a Metropolis-Hasting algorithm using the Planck 2018 CMB data , the Pantheon sample of SNIa data , a collection of Baryon Acoustic Oscillations (BAO) data , Cosmic Chronometer (CC) data , an up-to-date compilation of growth rate/redshift space distortions data.

$$\chi^2_{\rm tot} = \chi^2_{\rm CMB} + \chi^2_{\rm BAO} + \chi^2_{\rm SNIa} + \chi^2_{\rm CC} + \chi^2_{\rm KV450} + \chi^2_{\rm SZ} + \chi^2_{\rm WiggleZ}.$$



Results



M2
Param
M1
M2
M3
M4
CDM
Ω_m
H_0
S_8
0.30
0.32
67
68
69
0.75
0.80
0.74
0.77
0.83
−0.032
−0.036 +0.011 −0.017
−0.038
−0.037 +0.013 −0.020
S_8
0.794
0.790 ± 0.006

Results

$S_8 = 0.759^{+0.024}_{-0.021}$ from KiDS-1000

$$T_{S_8} = \frac{|S_8^i - S_8|}{\sqrt{\sigma_i^2 + \sigma^2}}$$

Model	M1	M2	M3	M4	CDM
T_{S_8}	0.58σ	0.23σ	0.50σ	0.15σ	1.25σ

The result of MCMC analysis for all reviewed models in this study for the best-fit χ^2

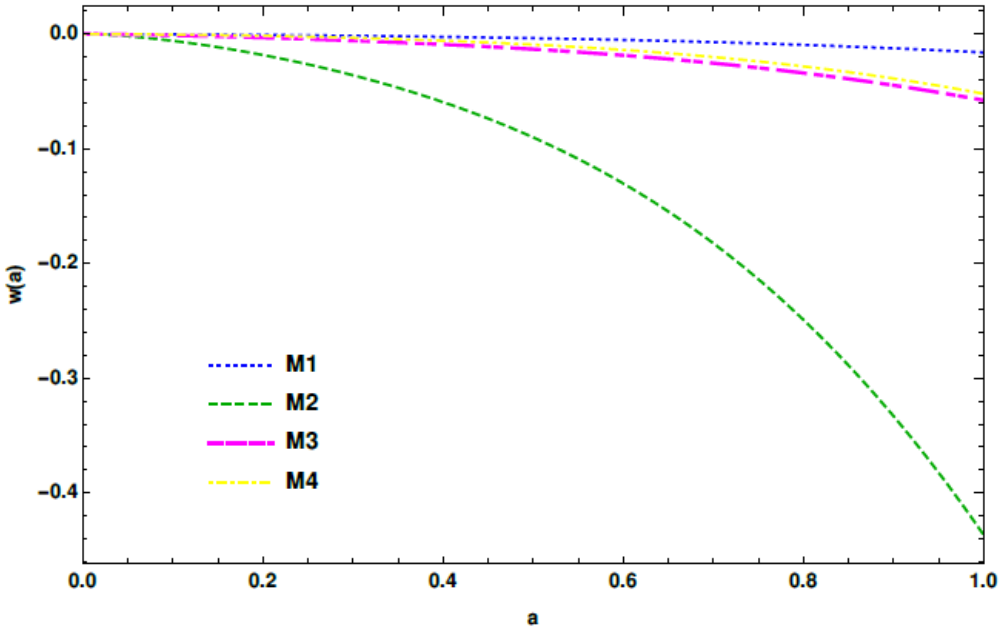
	Total data				
	M1	M2	M3	M4	CDM
$\chi^2_{\rm min}$	4848.68	4842.45	4842.20	4838.32	4855.87
AIC − $\rm AIC_{CDM}$	−5.518	−9.42	−9.67	−11.55	−

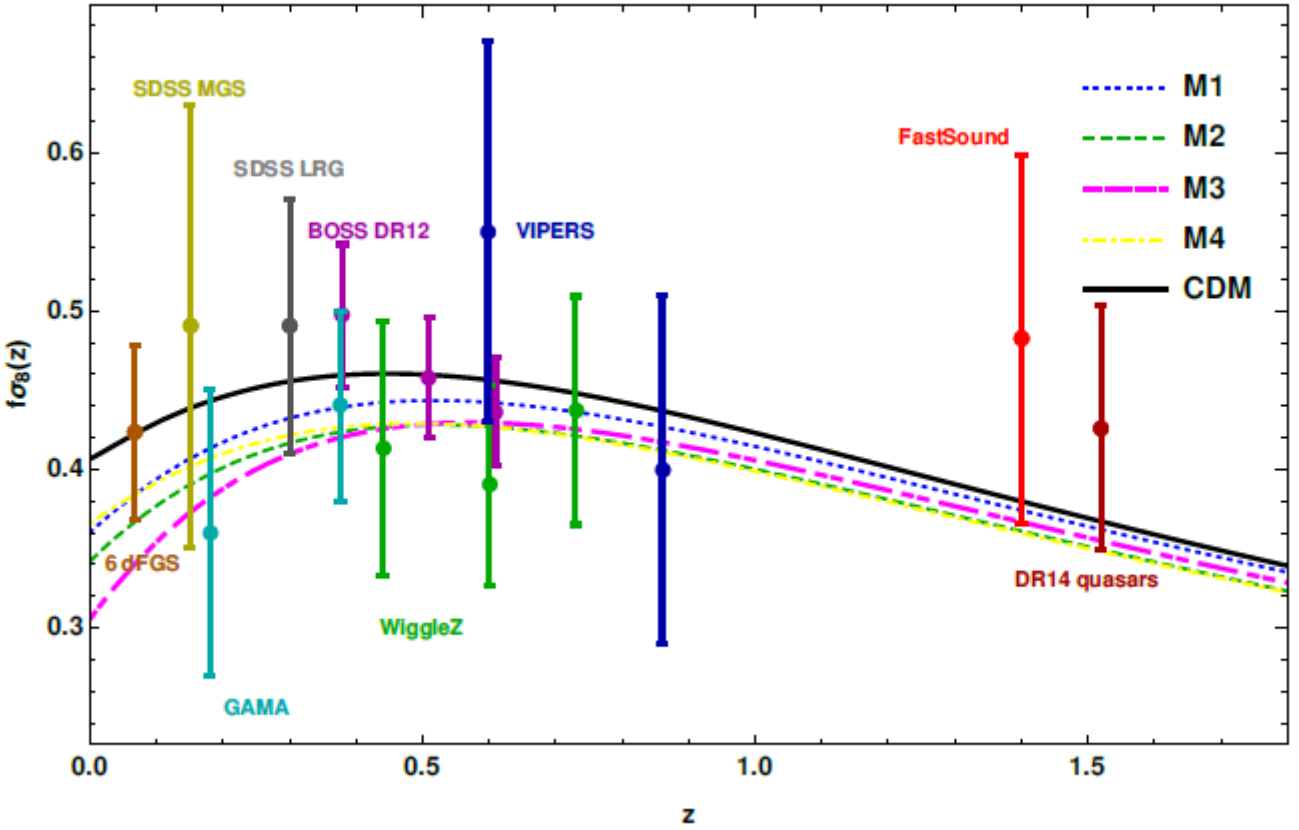
We see to add one, two, and three new parameters to the fit in the viscous dark matter scenarios, the AIC for them is much smaller than the CDM model. It shows an improvement of about 11.25, 9.67, 9.42 and 5.518 units of AIC relative to the CDM model for M4, M3, M2 and M1 scenarios, respectively.

Asgari, M., et al. 2021, A&A, 645, A104

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Results





In short, the effort to resolve cosmic tensions is still ongoing...

While the cosmic orchestra may be playing the symphony, somebody gave the bass and tuba the wrong score.

They're trying very hard to keep quiet about it.

We must demand an explanation.

Glenn Starkman



Thank you