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Interacting vacuum cosmology and observational constraints

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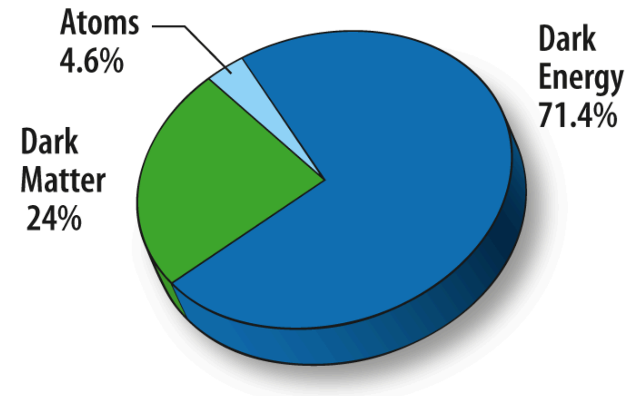
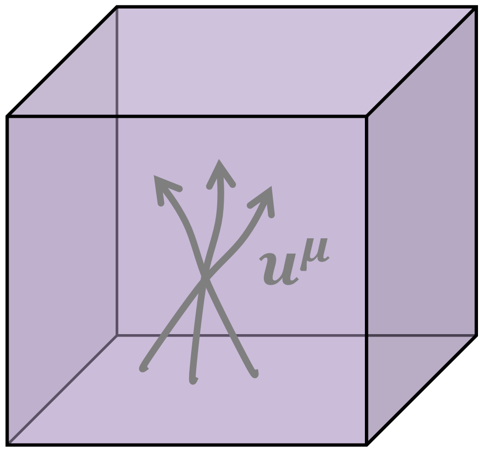
motivation:



- **parameterising dark energy in GR**
  - cosmological constant (*w* = -1, $Q = 0$, *V*=constant)
  - equation of state (*w* ≠ -1, $Q = 0$, $\rho_{DE}(z)$)
    - + interacting dark energy (*w* ≠ -1, $Q \neq 0$, $\rho_{DE}(z)$)
  - *interacting vacuum (w = -1, $Q \neq 0$, $V(z)$)*
- **test through cosmological observations**
  - *different perspectives on cosmological tensions*

simplest dark energy model

- **vacuum energy**
  - undiluted by expansion
  - no new degrees of freedom



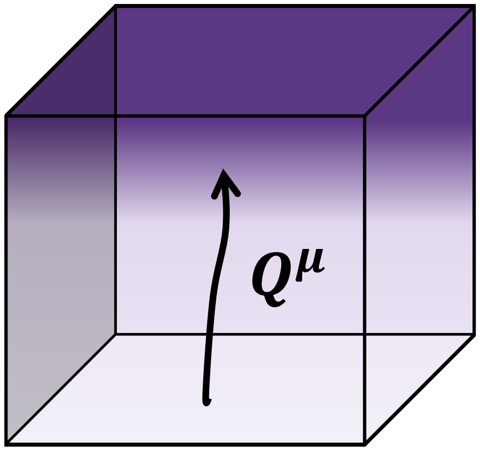
$$\check{T}^\mu_\nu = -V g^\mu_\nu$$

perfect fluid $$T^\mu_\nu = P g^\mu_\nu + (\rho + P) u^\mu u_\nu$$

with $$\check{\rho} = -\check{P} = V$$

no particle flow, hence 4-velocity, u^μ, undefined

energy-momentum flow



- **space-time dependent vacuum:**

$$Q_\nu \equiv \nabla_\mu \check{T}^\mu_\nu = -\nabla_\nu V$$

- **GR requires conservation of total matter+vacuum energy**

$$\nabla_\mu G_{\mu\nu} = 8\pi G_N \nabla_\mu \left(T^\mu_\nu + \check{T}^\mu_\nu \right) = 0 \quad \Rightarrow \quad \nabla_\mu T^\mu_\nu = -Q_\nu$$

  - special case: $Q_\nu = 0$ gives cosmological constant

interacting vacuum cosmology

homogeneous 3D space $\Rightarrow V = V(t), \;\; Q^{\mu} = (Q, \vec{0})$

Freese et al (1987); Berman (1991); Pavon (1991); Chen & Wu (1992);
Carvalho et al (1992); Al-Rawaf & Taha (1996);
Shapiro & Sola (2002); Sola (2011); …

- Continuity equations for matter + vacuum

$$\begin{aligned} \dot{\rho} + 3H(\rho + P) &= -Q\,, \\ \dot{V} &= Q\,. \end{aligned}$$

- simple models with one dimensionless parameter:
  - $Q = \alpha H \rho_m \quad \rightarrow \quad \rho_m \propto a^{-(3+\alpha)}$ decaying DM / running vacuum

    Shapiro et al (2003); Wang et al (2005); Alcaniz et al (2005); Gomez-Valent et al (2015)
  - $Q = -qHV \quad \rightarrow \quad V \propto a^{-q}$ decaying vacuum

    Salvatelli et al (2014); Martinelli et al (2018)
  - $Q = \frac{3\alpha' H \rho_m V}{(\rho_m + V)} \quad \rightarrow \quad \rho_m + V \propto \left(A + B a^{-3(1+\alpha')}\right)^{\frac{1}{1+\alpha'}}$ Chaplygin gas

    Bento, Bertolami & Sen (2005); Wang et al (2013)

interacting vacuum cosmology

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- Continuity equations for matter + vacuum

$$\begin{aligned} \dot{\rho} + 3H(\rho + P) &= -Q\,, \\ \dot{V} &= Q\,. \end{aligned}$$

Freedom to choose any $V(t)$

- *could just be a description rather than an explanation?*
- *distinguish physical models through perturbations…*

Bento, Bertolami & Sen (2006); Wang et al (2010)

vacuum fluid mechanics

Wands, De Santiago & Wang (2012)

inhomogeneous 3D space $\Rightarrow V(t,\vec{x}) = V(t) + \delta V\left(t,\vec{x}\right)$

$$Q^{\mu} = \left(Q + \delta Q, \vec{f}\right)$$

- energy conservation:

$$\delta\dot{V} \quad = \quad \delta Q$$

- momentum conservation:

$$\vec{\nabla}(-V) = \vec{\nabla} f$$

vanishing vacuum momentum requires vacuum pressure gradient balanced by force exerted on vacuum by matter

an equal and opposite force is exerted by the vacuum on matter

vacuum fluid mechanics

Wands, De Santiago & Wang (2012)

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- momentum conservation:

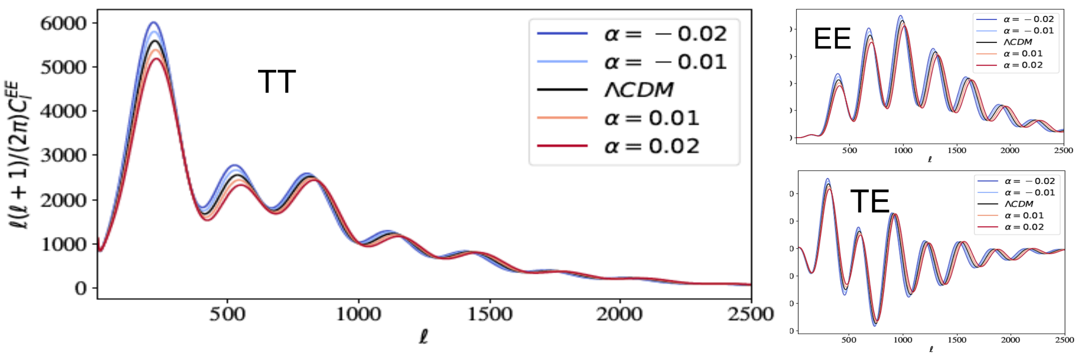
$$\vec{\nabla}(-V) = \vec{\nabla} f$$

simplest case: $Q^{\mu} \propto u_m^{\mu}$
zero momentum transfer in comoving frame
zero comoving vacuum perturbation
matter follows geodesics

vanishing vacuum momentum requires vacuum pressure gradient balanced by force exerted on vacuum by matter

an equal and opposite force is exerted by the vacuum on matter

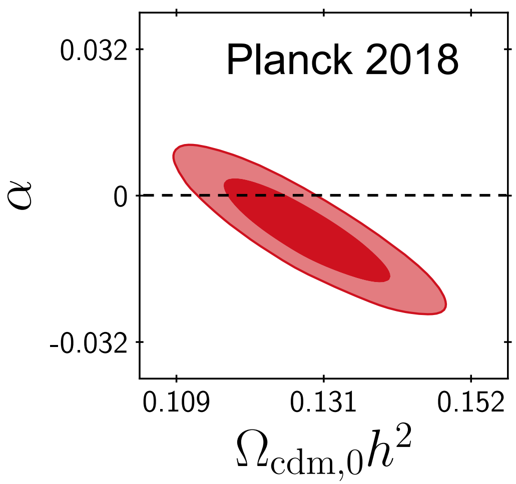
CMB power spectra: *geodesic model*



CMB fixes matter density at last scattering
$Q > 0$ decreases matter density after last-scattering

increases redshift of matter-dark energy equality
fixed horizon size ⇒ increases H_0

and increases σ_8

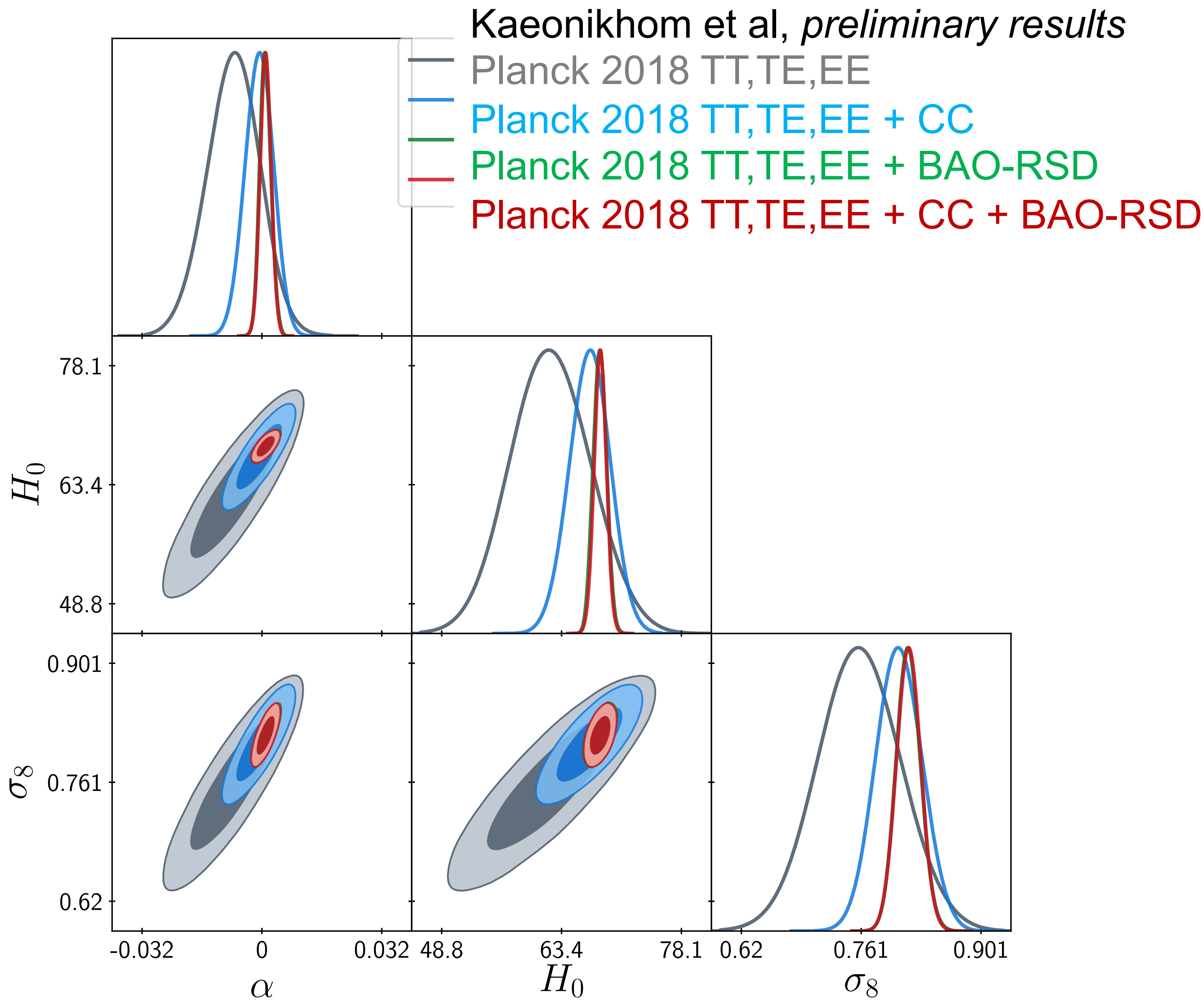


decaying DM: $Q = \alpha H \rho_m$

Kaeonikhom, Assadullahi, Schwetschenko & Wands, in prep

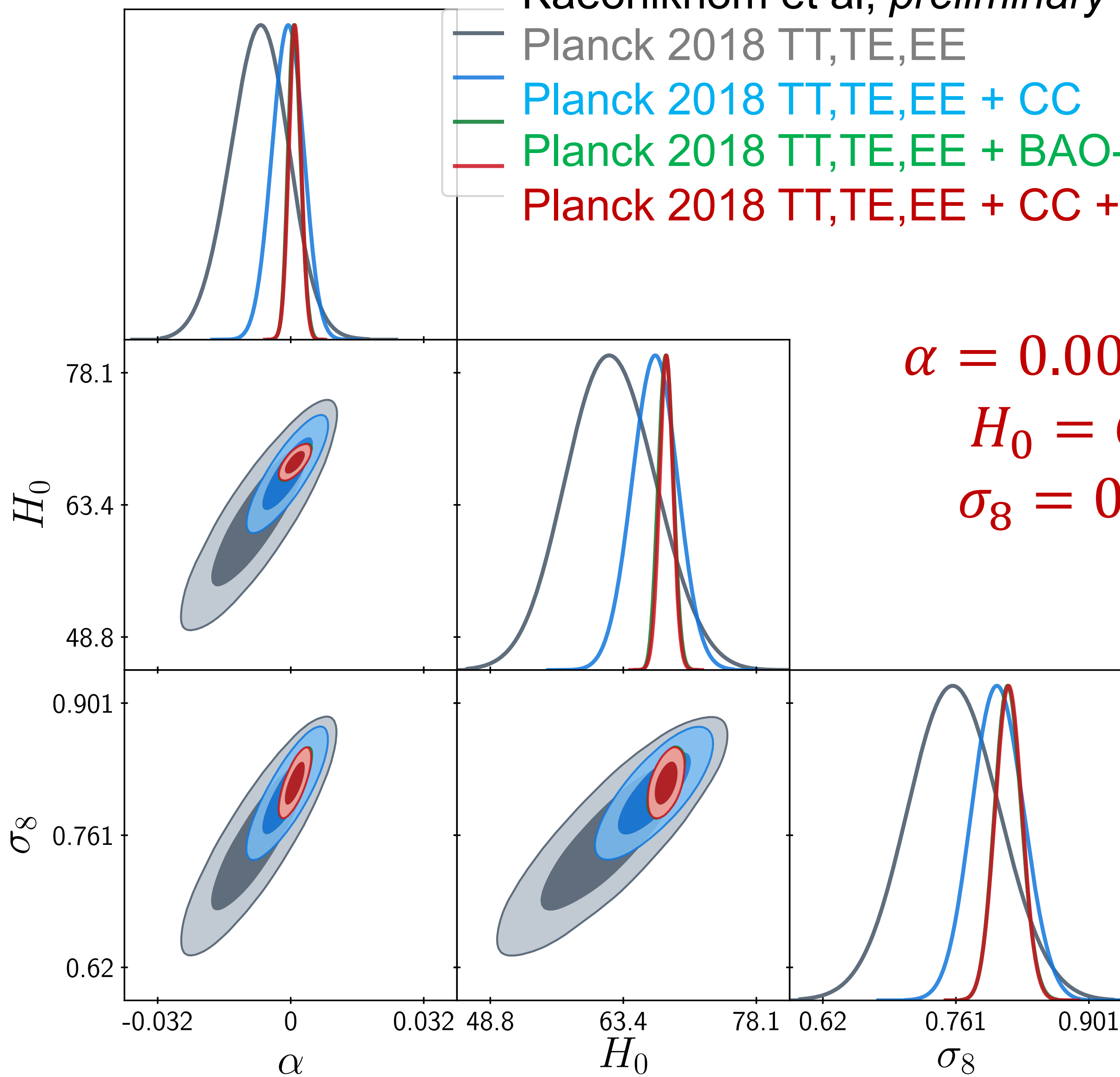
see also Gomez-Valent et al (2015); Sola et al (2021)

geodesic decaying DM $Q = \alpha H \rho_m$



geodesic decaying DM $\quad Q = \alpha H \rho_m$

Kaeonikhom et al, *preliminary results*



$$\alpha = 0.0010 \pm 0.0015$$
$$H_0 = 68.2 \pm 0.8$$
$$\sigma_8 = 0.82 \pm 0.01$$

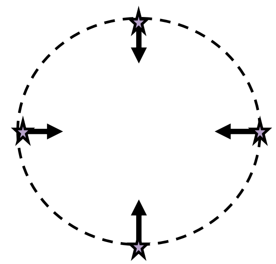
ΛCDM Planck+BAO:

$$H_0 = 67.7 \pm 0.4$$
$$\sigma_8 = 0.81 \pm 0.01$$

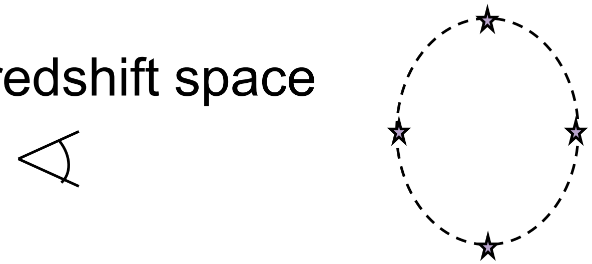
redshift space distortions

peculiar velocities along line of sight lead to apparent distortions in galaxy power spectrum inferred from redshifts

real space



redshift space



for *non-interacting* matter the velocity divergence can be identified with growth of structure

$$\dot{\delta}_m = -\vec{\nabla} \cdot \vec{v}_m \,, \quad \Rightarrow \quad \langle (\vec{\nabla} \cdot \vec{v}_m)^2 \rangle = \langle \dot{\delta}_m^2 \rangle \sim (f \sigma_8)^2$$

but, for *interacting* matter energy transfer also contributes

$$\dot{\delta}_m = -\vec{\nabla} \cdot \vec{v}_m + \frac{\dot{V}}{\rho_m} \delta_m \,, \quad \Rightarrow \quad \langle (\vec{\nabla} \cdot \vec{v}_m)^2 \rangle = \langle \left(f - \frac{\dot{V}}{\rho_m} \right)^2 \delta_m^2 \rangle$$

Wang et al (2015)
Borges & Wands (2017)

outstanding challenges

- **theoretical basis**
  - any dark energy $w(z)$ can be decomposed into interacting matter+vacuum
  - but what is underlying microphysics?
  - can it describe $w \to -1$ limit of dynamical dark energy?

- **how to make model-independent tests?**
  - switch on/off interaction, $\mathrm{Q}(z)$ Salvatelli et al (2014); Sola et al (2021)
  - principal component analysis Wang et al (2015); Hogg et al (2020)

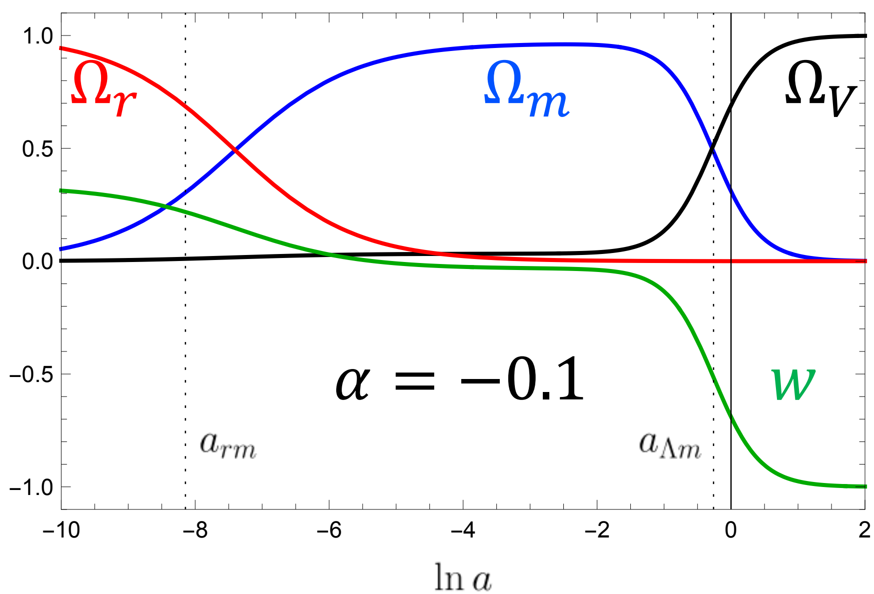
- **phenomenology**
  - degeneracy between Q and H_0 can ease CMB tension with high H_0
  - but increasing H_0 tends to increase σ_8
  - note that redshift space distortions not same as growth of structure, $f\sigma_8$, in presence of interaction

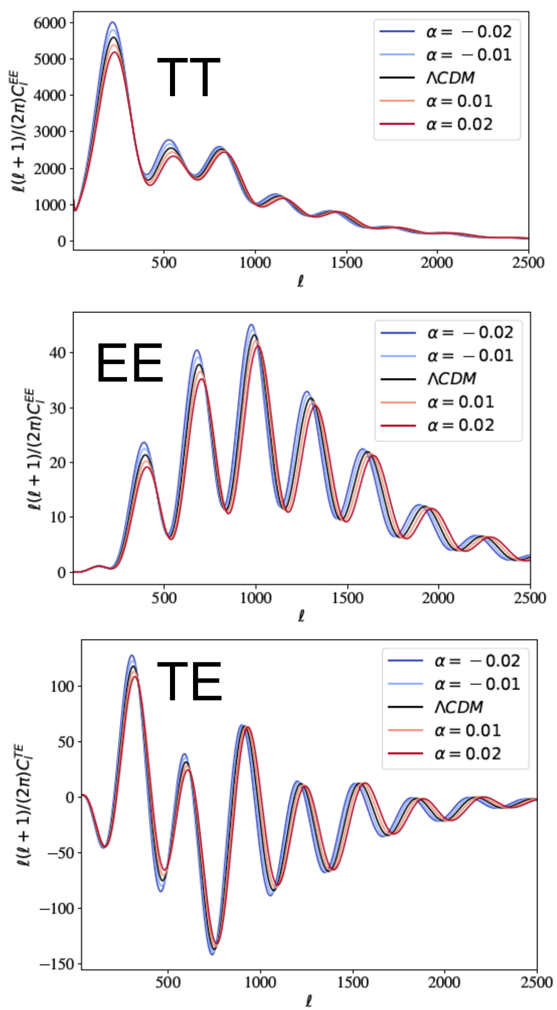
bonus slides

geodesic decaying dark matter

Kaeonikhom, Assadullahi, Schwetschenko & Wands, in prep

$$Q = \alpha H \rho_m \,, \quad \delta V_{\rm com} = 0$$





geodesic decaying DM

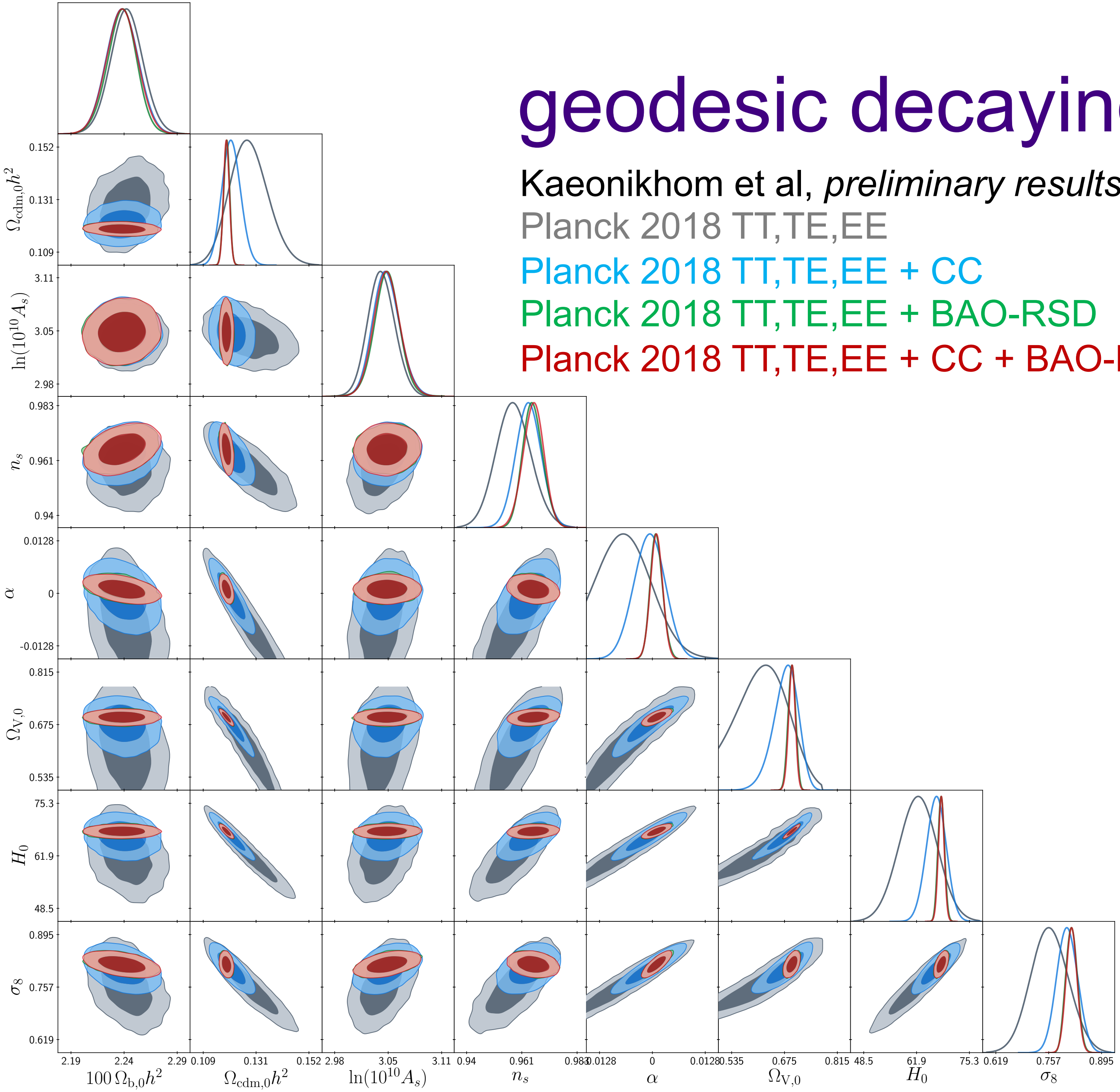
Kaeonikhom et al, *preliminary results*

Planck 2018 TT,TE,EE

Planck 2018 TT,TE,EE + CC

Planck 2018 TT,TE,EE + BAO-RSD

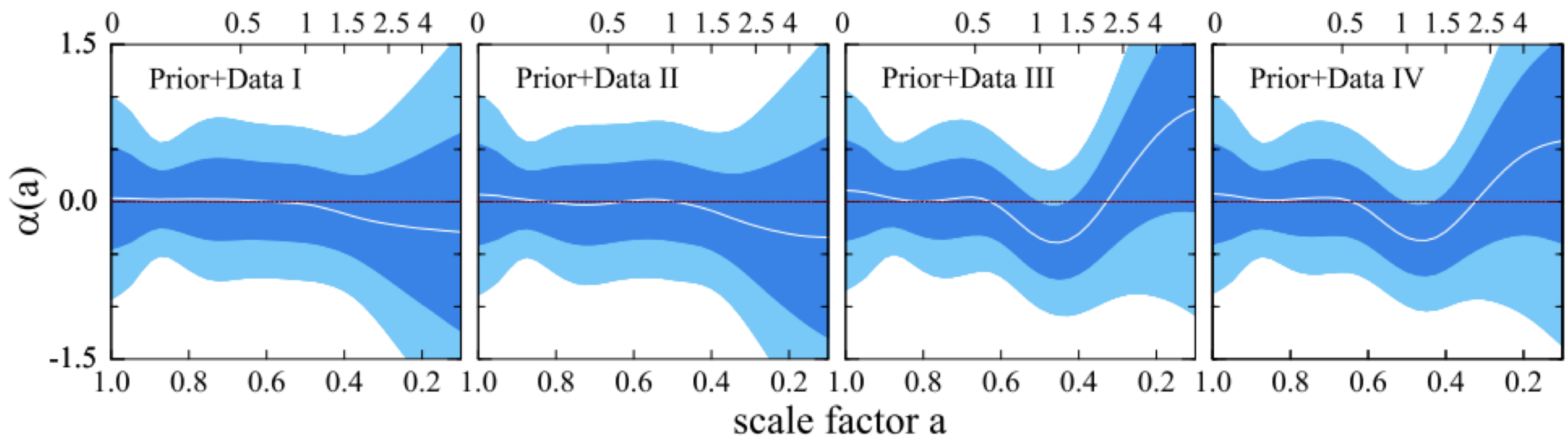
Planck 2018 TT,TE,EE + CC + BAO-RSD

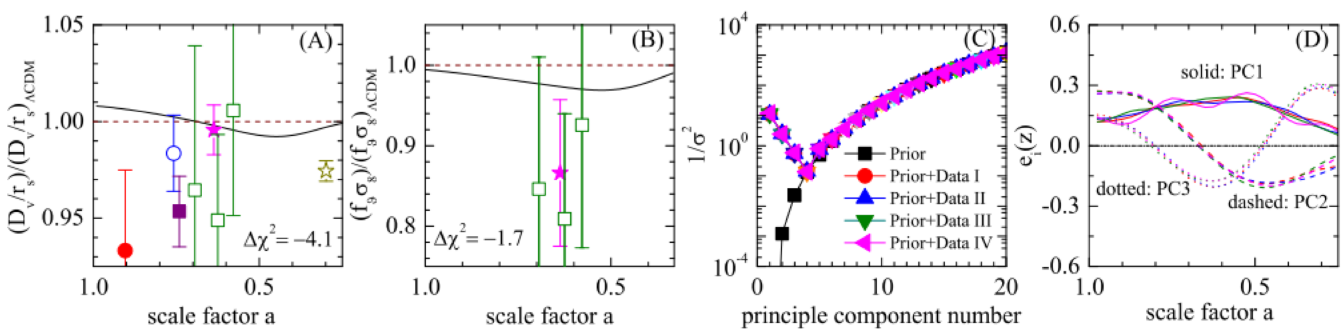


Reconstructing Q(z)

Wang, Zhao, Wands, Pogosian & Crittenden (2015)

$$Q(z) = \frac{3H\rho_m V}{\rho_m + V}\alpha(z)$$





Reconstructing Q(z)

Hogg, Bruni, Crittenden, Martinelli & Peirone (2020)

$$Q(z) = -q(z)HV$$

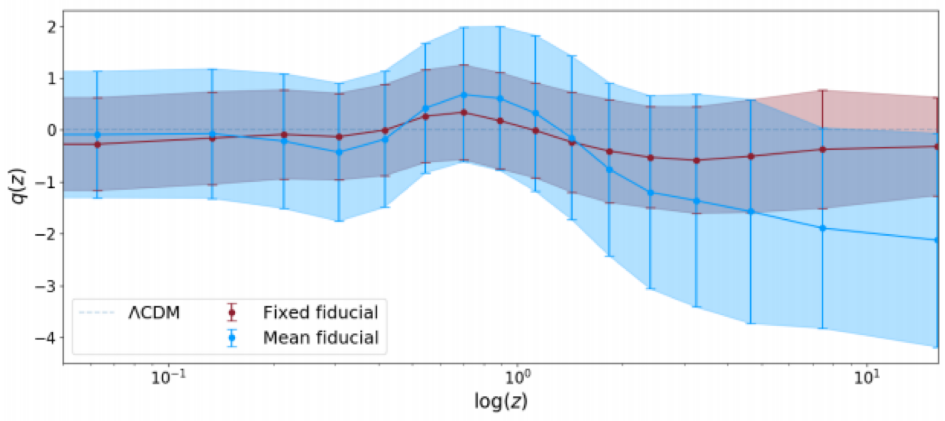


Figure 3: The results of the cubic spline reconstruction of the coupling function $q(z)$. Red and blue lines and areas refer to the fixed fiducial and mean fiducial cases respectively, and the shaded areas denote the 1σ confidence interval.

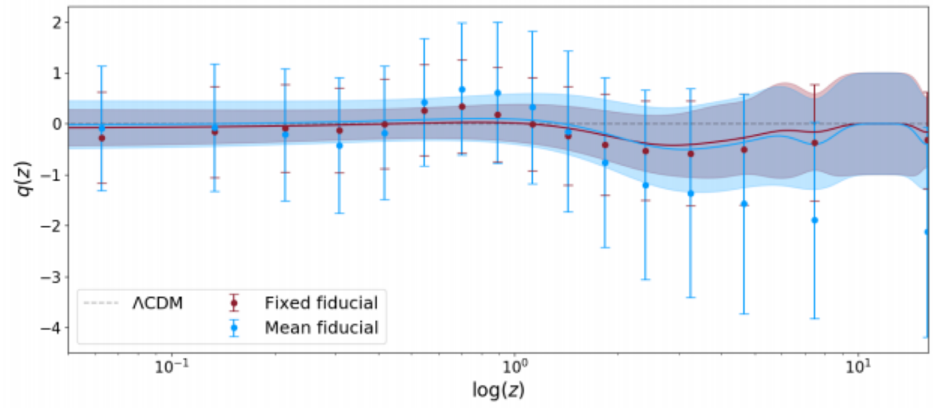
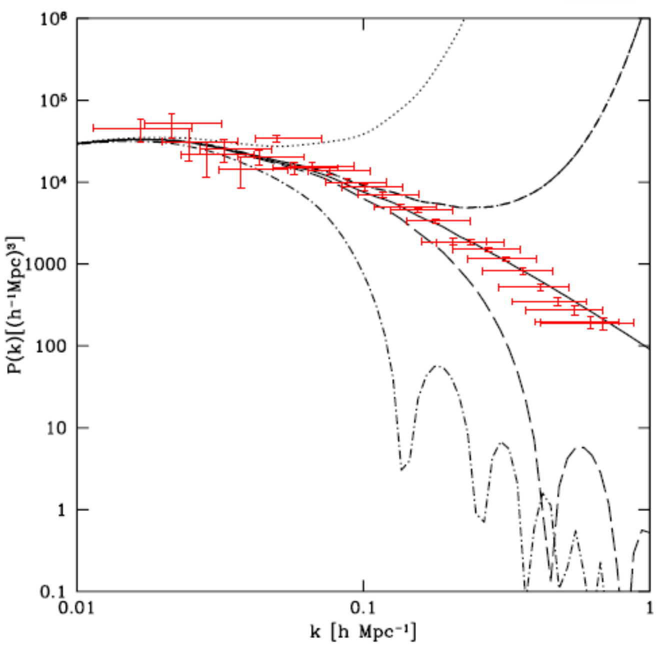


Figure 4: The results of the Gaussian process reconstruction of the coupling function $q(z)$. Red and blue lines and areas refer to the fixed fiducial and mean fiducial cases respectively, and the shaded areas denote the 1σ confidence interval.

different physical models:

matter power spectrum

- **Barotropic model**: $\boldsymbol{V = V(\rho_m)}$
  - *adiabatic vacuum perturbation:*
  $$\delta V = -\left(\frac{Q}{3H\rho_m + Q}\right)\delta\rho_m$$
  - *coupled sound speed:*
  $$c_s^2 = \frac{\dot{P}}{\dot{\rho}} = \frac{-\dot{V}}{\dot{\rho}_m + \dot{V}} = \frac{Q}{3H\rho_m}$$



barotropic unified dark models very tightly constrained by matter power spectrum

$$|\alpha'| < 10^{-6}$$

Sandvik et al (2002)

different physical models Wands, De Santiago & Wang (2012)

- **Barotropic model**: $V = V(\rho_m)$
  - *adiabatic vacuum perturbation:* $$\delta V = -\left(\frac{Q}{3H\rho_m + Q}\right)\delta\rho_m$$
  - *coupled sound speed:* $$c_s^2 = \frac{\dot{P}}{\dot{\rho}} = \frac{-\dot{V}}{\dot{\rho}_m + \dot{V}} = \frac{Q}{3H\rho_m}$$
- **Geodesic model**: $Q_\nu = Q\, u_\nu$
  - *zero momentum transfer in comoving frame:* $f = -\delta V_{\rm com} = 0$
  - *zero sound speed:* $$c_s^2 = \left(\frac{\delta P}{\delta\rho}\right)_{\rm com} = 0$$

matter power spectrum: *geodesic perturbations*