Interacting Vacuum
&
Tensions

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Outline

- ΛCDM and beyond
- Interacting Vacuum scenario
- observational constraints on IV: two examples
- evolution of IV models and perturbations and tensions
- Conclusions

Credits: Natalie Hogg, Robyn Munoz and many others

Standard ΛCDM Cosmology

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- Recipe for modelling based on 3 main ingredients:
  1. Homogeneous isotropic background, FLRW models
  2. Relativistic Perturbations, good for early times and/or for large scales, e.g. CMB and LSS; I-order, II order, "gradient expansion" (aka long-wavelength approximation)
  3. Newtonian study of non-linear structure formation (N-body simulations or approx. techniques, e.g. 2LPT) at small scales

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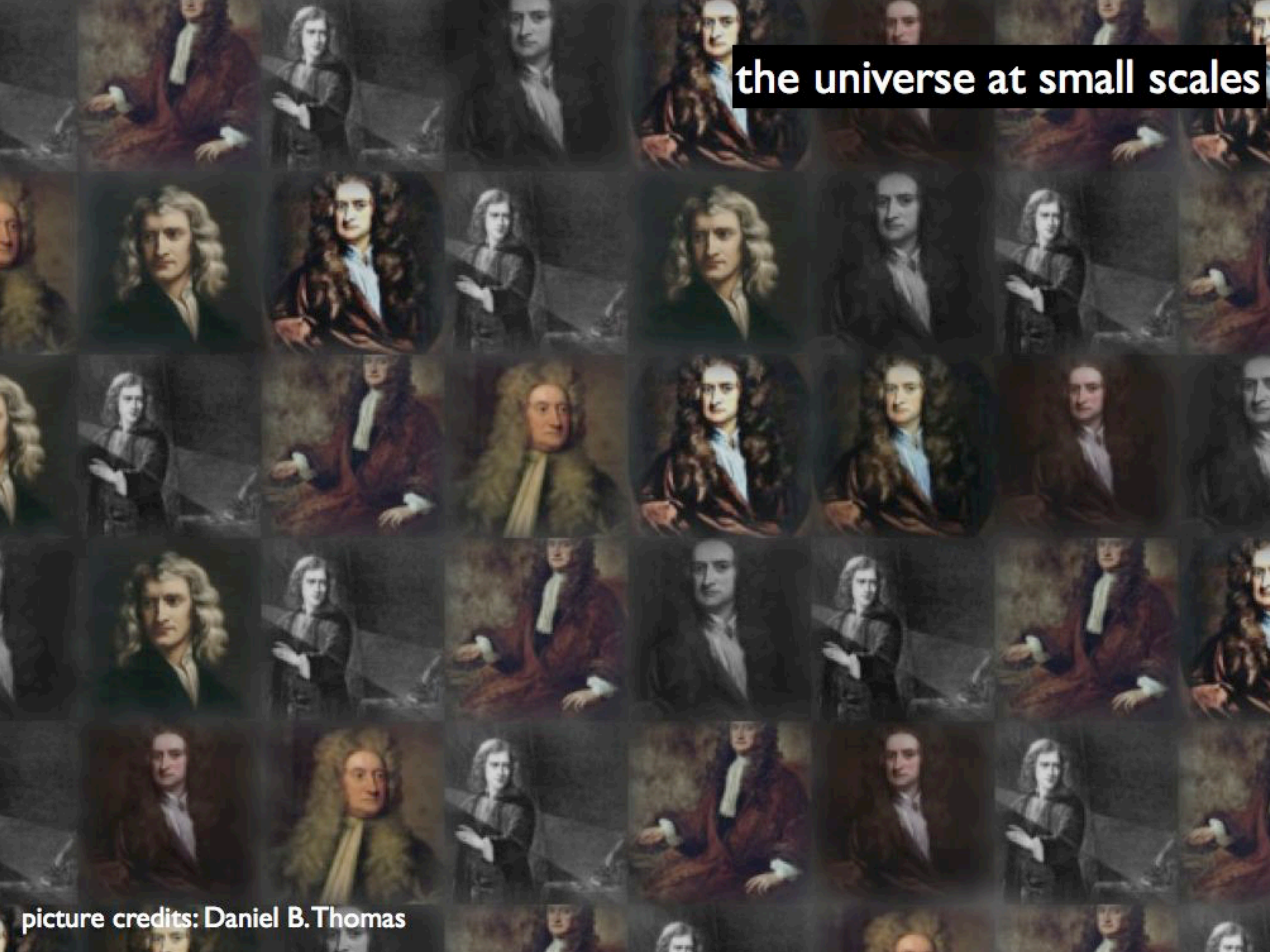
- on this basis, well supported by observations, the flat ΛCDM model has emerged as the Standard "Concordance" Model of cosmology.

the universe at very large scales: GR

picture credits: Daniel B. Thomas


the universe at small scales
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beyond ΛCDM

- ΛCDM is the simplest and very successful model supporting the observations that, assuming the Cosmological Principle, are interpreted as acceleration of the Universe expansion
- ΛCDM: Λ accelerates the expansion, Cold Dark Matter (CDM) drives structure formation
- Tensions and theoretical considerations lead to explore alternatives

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   b) modified gravity (f(R), branes, etc…)

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    b) consider inhomogeneous models, e.g. LTB (violating the CP) or Szekeres (not necessarily violating the CP): back-reaction on observations (for LTB see e.g. Kenworthy et al 1901.08681 and Camarena et al 2205.05422)

beyond ΛCDM standard recipe

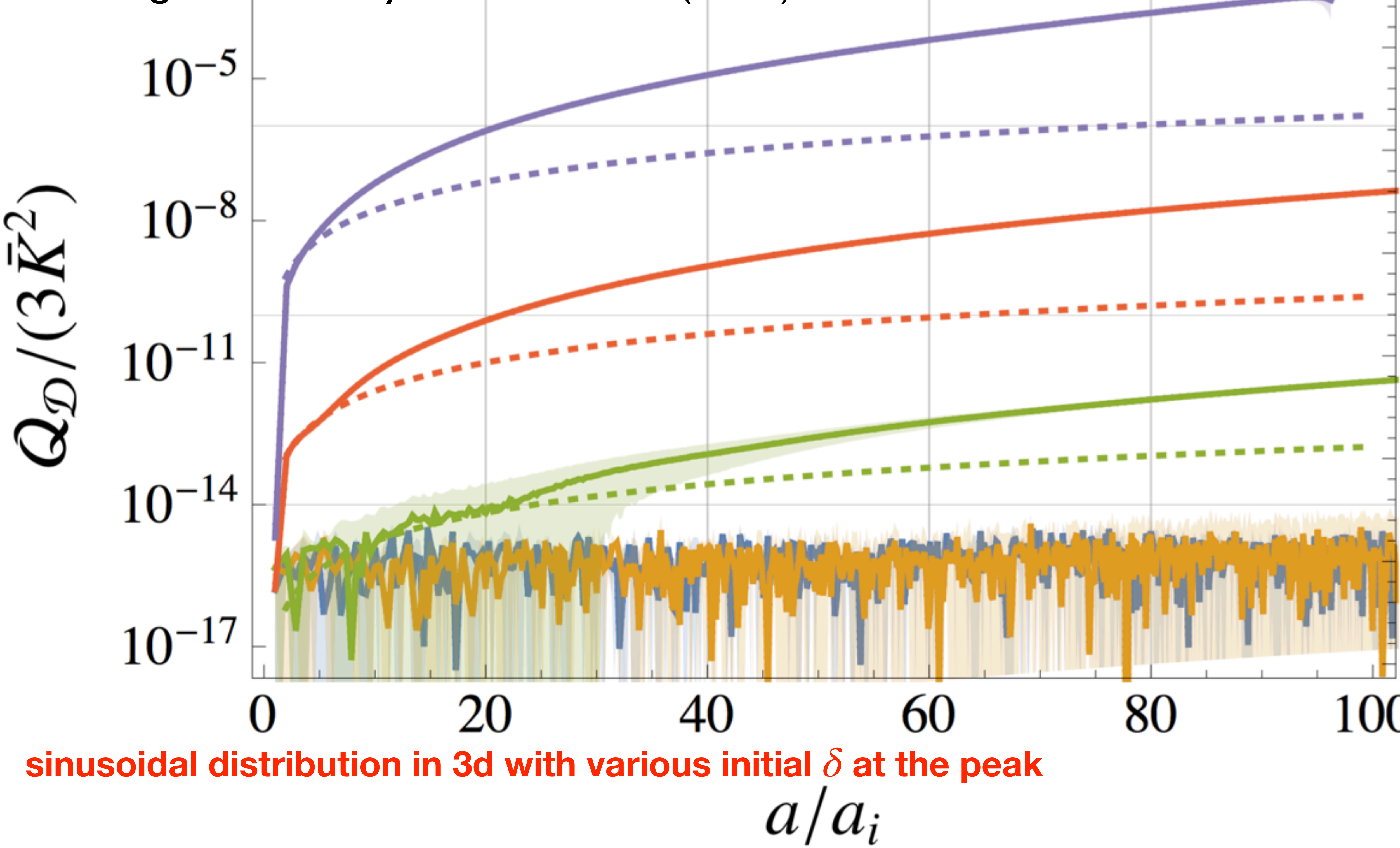
3. NEW: stick with ΛCDM, but use fully nonlinear GR, i.e. Numerical Relativity simulations

   i) Full GR equations: Bentivegna & MB, 1511.05124, Giblin et all 1511.01105, Macpherson et al 1807.01714, Heinesen et al 2111.14423, Dhawan et al 2205.12692 (this last 3 related to H_0)

   ii) Full GR N-body, with some approximation (post-Friedmann, or neglect tensor modes): MB, Thomas and Wands 1306.1562; Adamek et al 1509.01699, 1604.06065, Barrera-Hinojosa, Li, MB & He 2010.08257

backreaction: Ω_Q

Bentivegna & MB, Phys.Rev.Lett. 116 (2016) 25, 251302 1511.05124



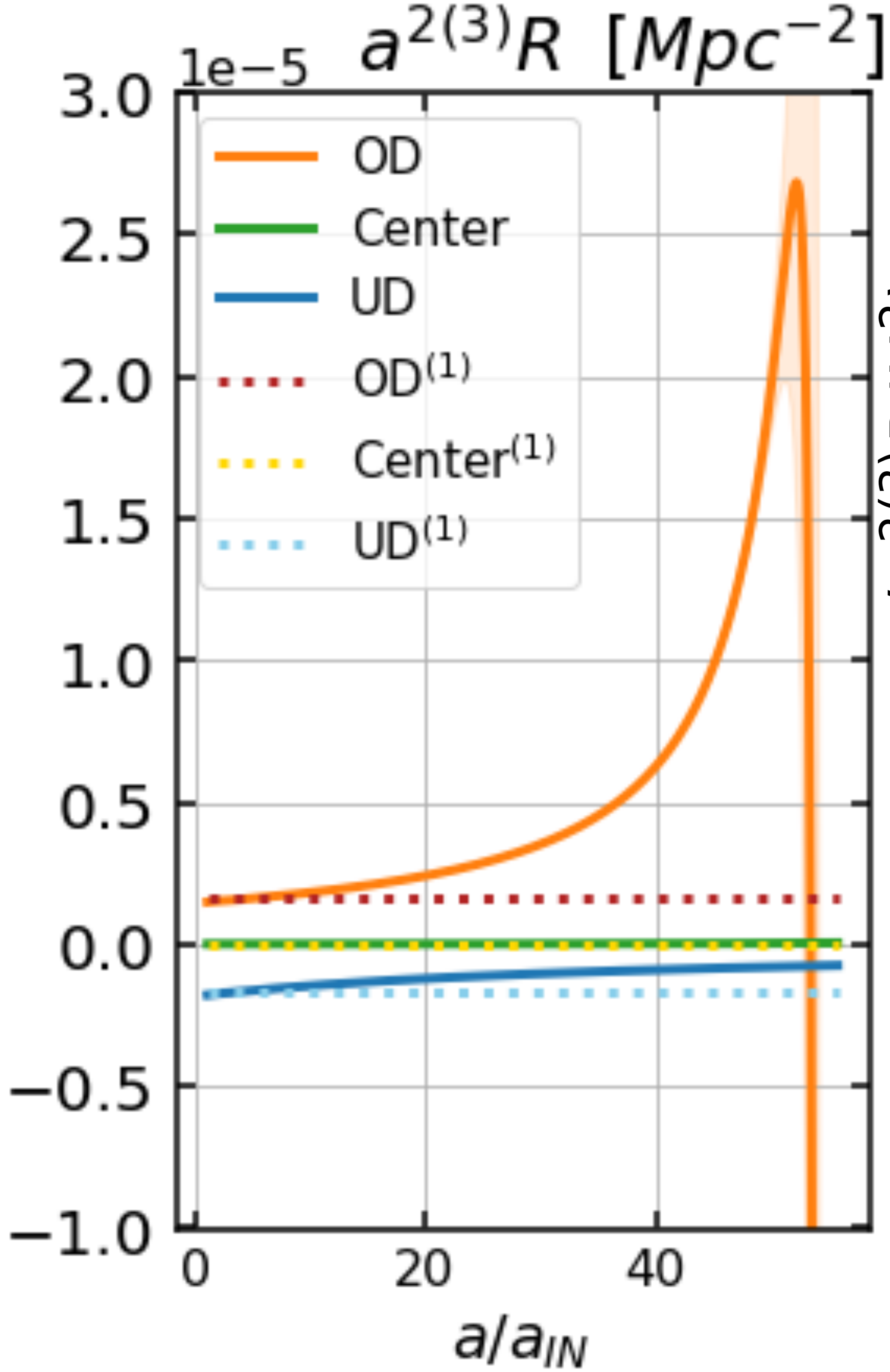
sinusoidal distribution in 3d with various initial δ at the peak

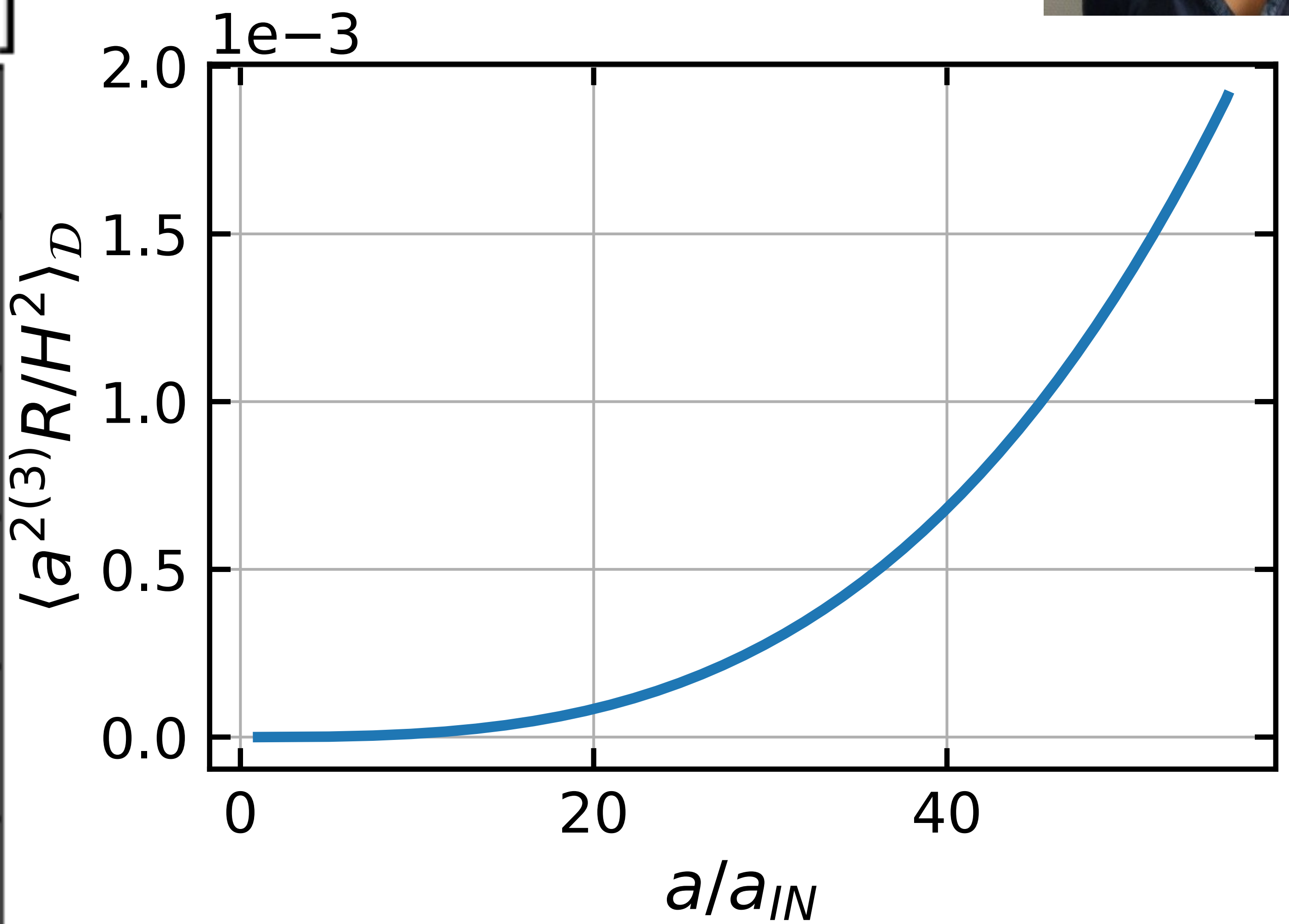
work in progress

ΛCDM simulations by PhD student Robyn Munoz

initial δ at peak: 0.03
Box size: 1821Mpc
initial redshift: 302.5
end redshift: 4.43

warning: sync comoving gauge





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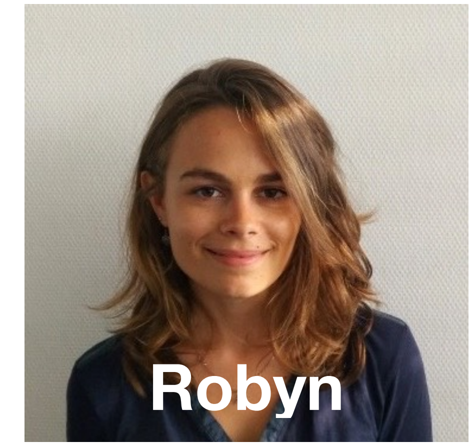

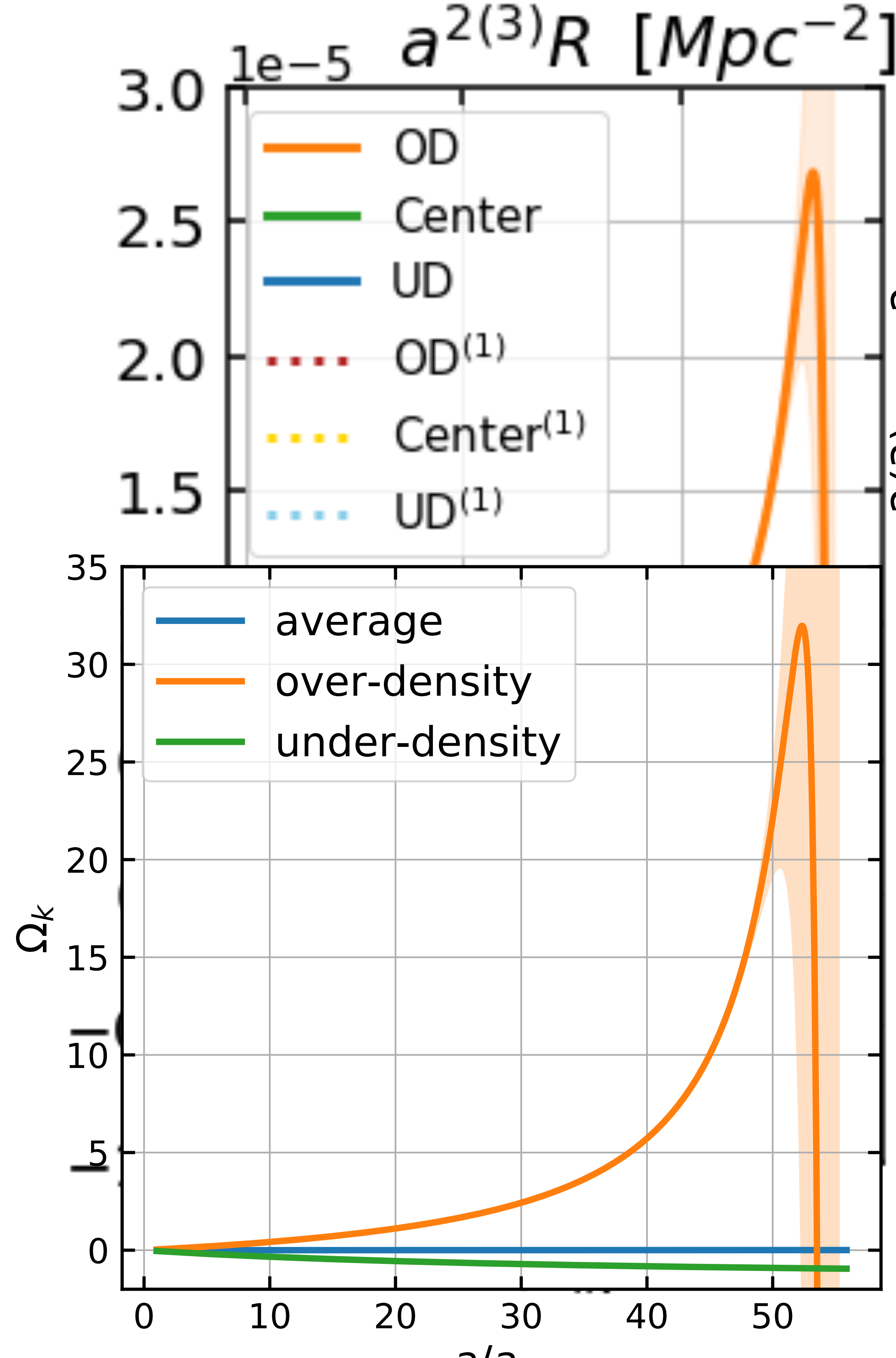

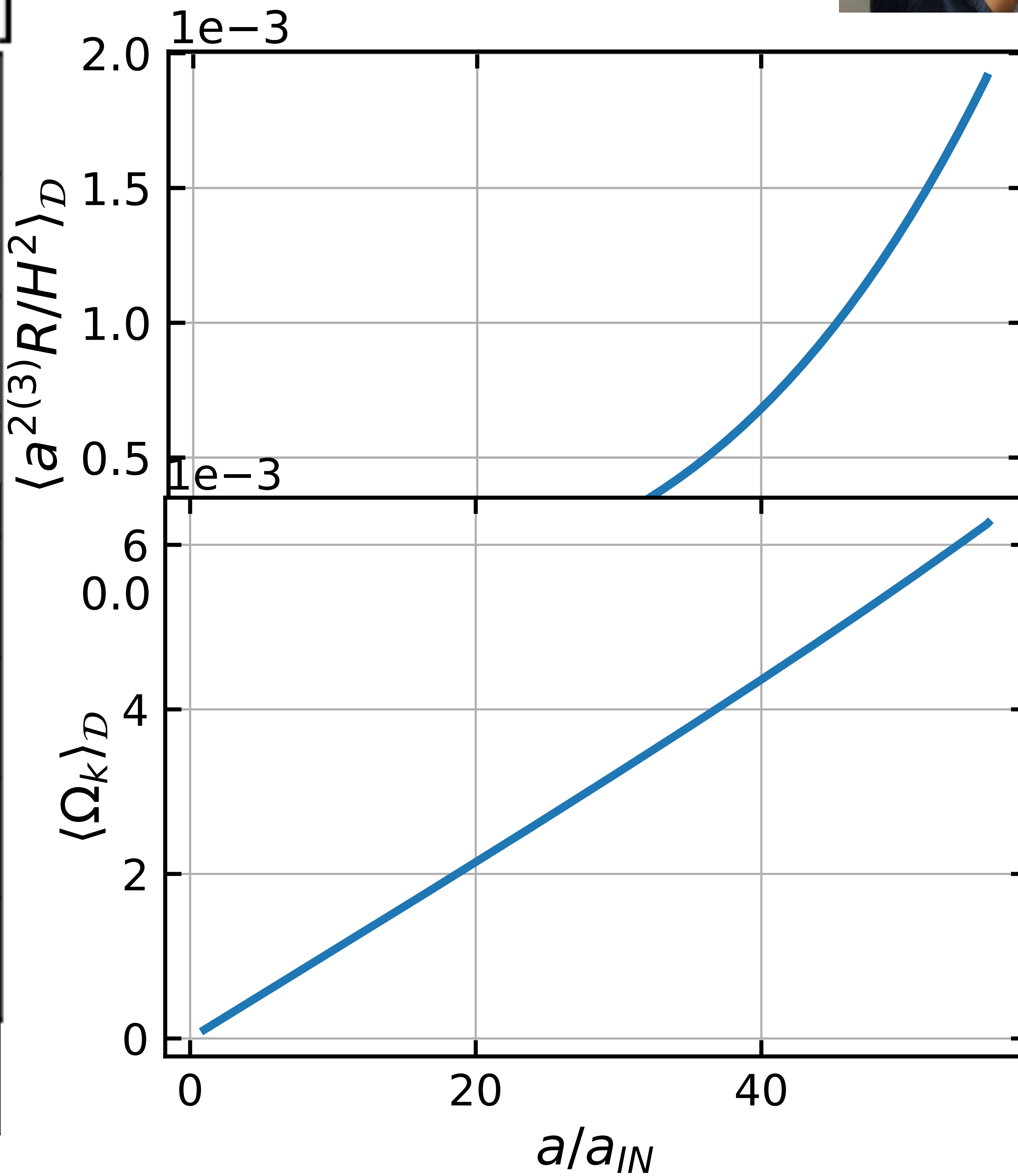

Interacting Vacuum Scenario

- Phenomenological approach, attempt to reconcile measurements allowing for an interaction in the Dark Sector, coupling together CDM and vacuum energy.

- Interesting for several reasons:
  - it introduces a natural evolution of vacuum energy density: it can help with the coincidence problem.
  - it modifies both background and perturbation evolutions, thus it changes the assumptions we use to propagate high redshift measurements to low redshift parameters (S_8, H_0): it has a chance to ease the "tensions"
  - No additional propagating degrees of freedom
  - No modifications of GR is required
  - Bouncing cosmologies are allowed, MB Mayer & Wands 2111.01765

CDM-Vacuum interaction

$$T^{\mu}_{\nu}(\mathrm{mat}) = \rho_c u^{\mu} u_{\nu} \qquad T^{\mu}_{\nu}(\mathrm{vac}) = -V g^{\mu}_{\nu}$$

Λ if there is no coupling

- total Energy-Momentum is conserved, but CDM and Vacuum are coupled:

$$\nabla_{\mu} T^{\mu}_{\nu}(\mathrm{mat}) = -Q_{\nu} \qquad \nabla_{\mu} T^{\mu}_{\nu}(\mathrm{vac}) = Q_{\nu}$$

- In general $Q^{\mu} = Q u^{\mu} + f^{\mu}$, but we assume the simplest possible form of interaction, a pure exchange of energy in the frame of CDM $Q^{\mu} = Q u^{\mu}$
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see 2107.03235 for IV models with momentum transfer

Perturbations in the geodesic scenario

- when $Q^\mu = Qu^\mu$ we only have an energy exchange in the CDM rest frame
- the net result is that Vacuum is homogenous in the slicing orthogonal to u^μ
- we can choose a gauge in this slicing, the obvious one being synchronous comoving, and both the Vacuum and the interactions are unperturbed in this gauge
- The unperturbed coupling Q enters in the background conservation equations and in the equation for the matter perturbation $\delta = \delta\rho/\rho$, not in the one for $\delta\rho$

RSD in integrating scenarios

- standard growth rate is $f \equiv \dfrac{d \ln D}{d \ln a}$
- in interacting models Q enters the equation for δ, thus this modifies the growth rate to $f_i \equiv f - \dfrac{Q}{H\rho}$
- the unmodified version of CAMB would compute $f\sigma_8$
- a modified version of CAMB for interacting models would compute $f_i\sigma_8$
- hence this parameter is an indirect measure of the growth rate: we can safely use RSD data to constrain the interaction strength, however this is not a direct constraint on the growth factor f

CDM-Vacuum interaction

- Two approaches:

  1. binning and reconstruction (as in Silvestri talk)

  2. assume a specific model for the interaction

- I will present an example for each case:

  1. Martinelli, Hogg, Peirone, MB & Wands 1902.10694,
     Hogg, MB, Crittenden, Martinelli & Peirone 2002.10449

  2. Hogg and MB, 2109.08676

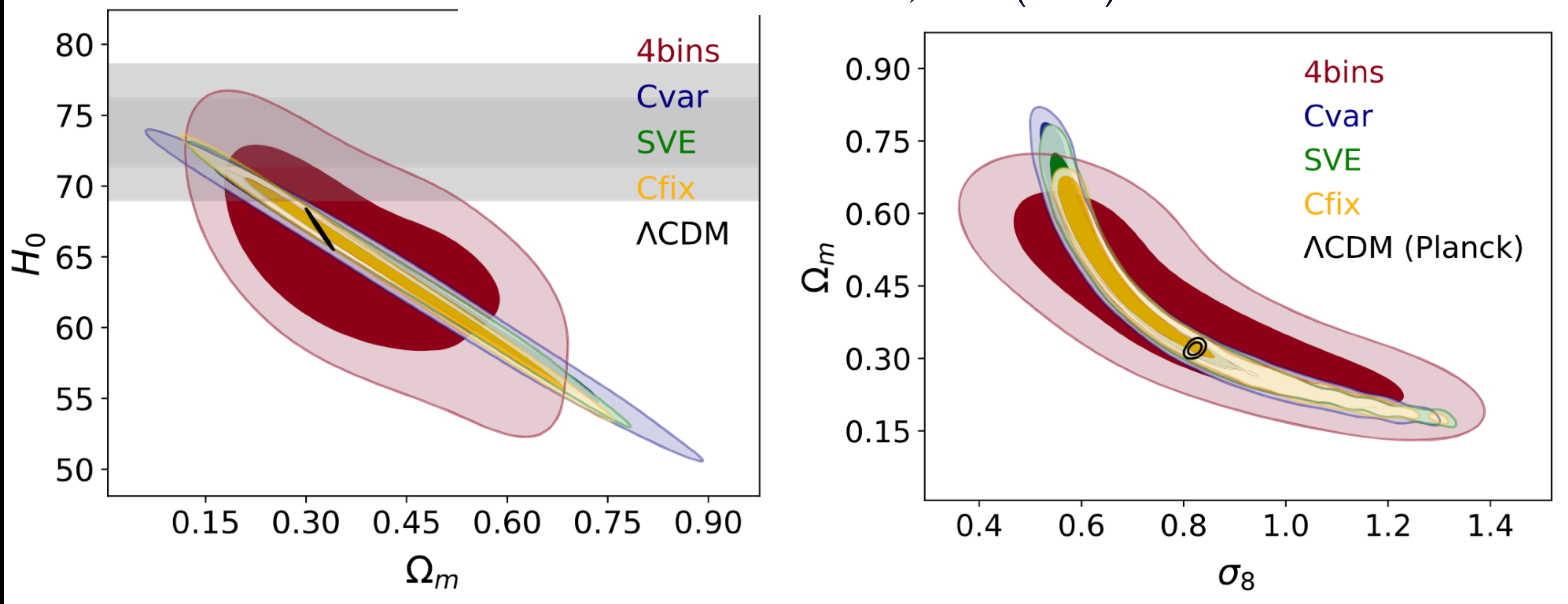
1) Reconstruction

$$Q(z) = -q_V(z)H(z)V$$

- simple choice, q_V dimensionless parameter, function of redshift z
- subclass of couplings linear in the energy densities.
  The model is therefore fully described by choice of the standard cosmological parameters and by the coupling function $q_V(z)$.
- dependence from Hubble expansion scalar H(z) actually ensures that the evolution of the two components only depends from the expansion (as in the non interactive adiabatic expansion for CDM) and it is decoupled from Friedmann equation

simplest models for $q_V(z)$

Martinelli *et al* MNRAS 488, 3423 (2019)



- similar constrains on all but the 4-bins model, an effect which is due to the higher number (4) of coupling parameters and their degeneracies with the standard cosmological ones.
- apparently ease the tension between the local measurements of H_0 (grey band) and the Planck measurement. However, this is only due to the extreme degeneracy between H_0, Ω_m, and q_V
- the tension is eased only because of the much larger error bars
- reconciling the tension in σ_8 is less feasible in this model.
- Lower values of σ_8 are allowed, but these lower values subsequently necessitate higher values of Ω_m in compensation, which are then disfavoured by the Low-z data.

2) Shan-Chen-type interaction

Hogg and MB, 2109.08676

- equation of state originally developed in the context of lattice kinetic theory

$$w_{\rm eff} = \frac{P(\rho)}{\rho} = w + \frac{w g \rho_*}{2\rho}(1 - e^{-\alpha \frac{\rho}{\rho_*}})^2.$$

- can be turned into an interaction Q:

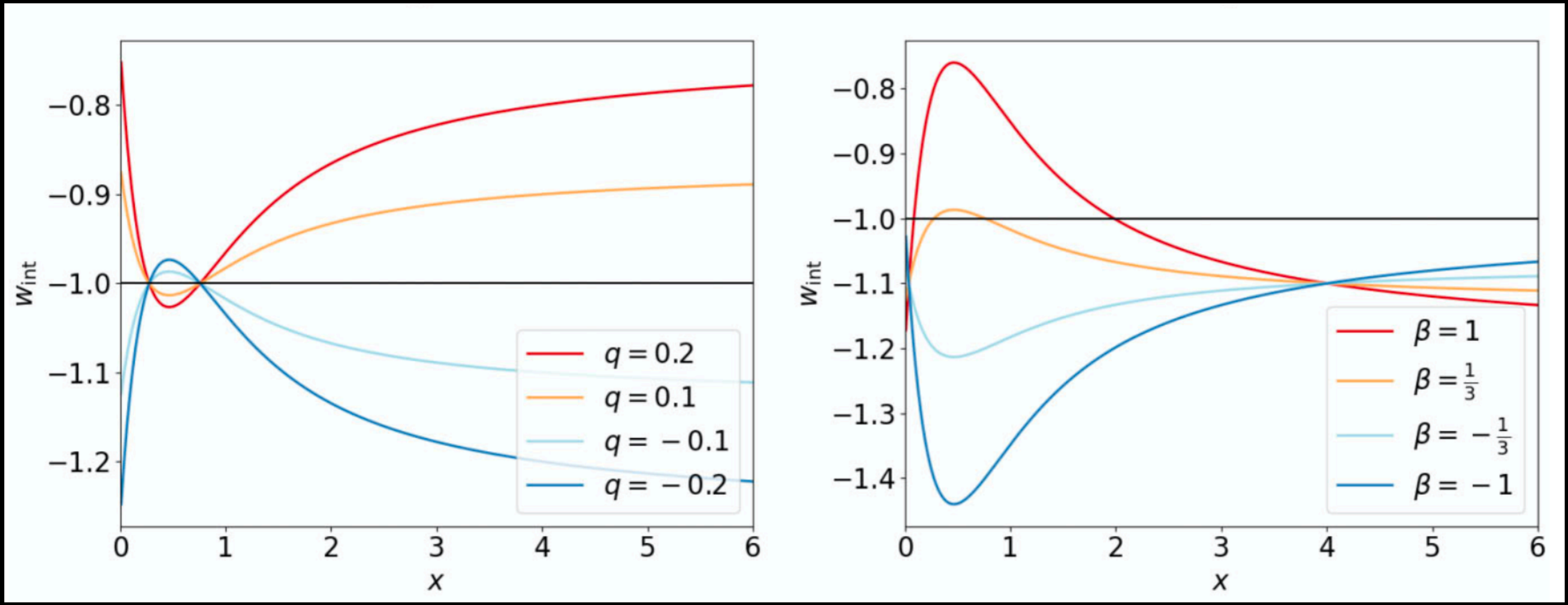
$$Q = \dot{V} = -3HV(1 + w_{\rm int}),$$

- where we can define an “w(z) for the interaction”, with $x = \rho/\rho_*$ and *q* interaction strength parameter

$$w_{\rm int} = q(1+\beta) + \frac{q\beta g}{2x}\left(1 - e^{-\alpha x}\right)^2 - 1,$$

2) Shan-Chen-type interaction

- α, β and g extra parameters that allow for many different dynamics
- we fix $\alpha = 2.7$ and $g = -8$ (Bini *et al* 2013, background only)
- Vacuum *V* can either growth or decay



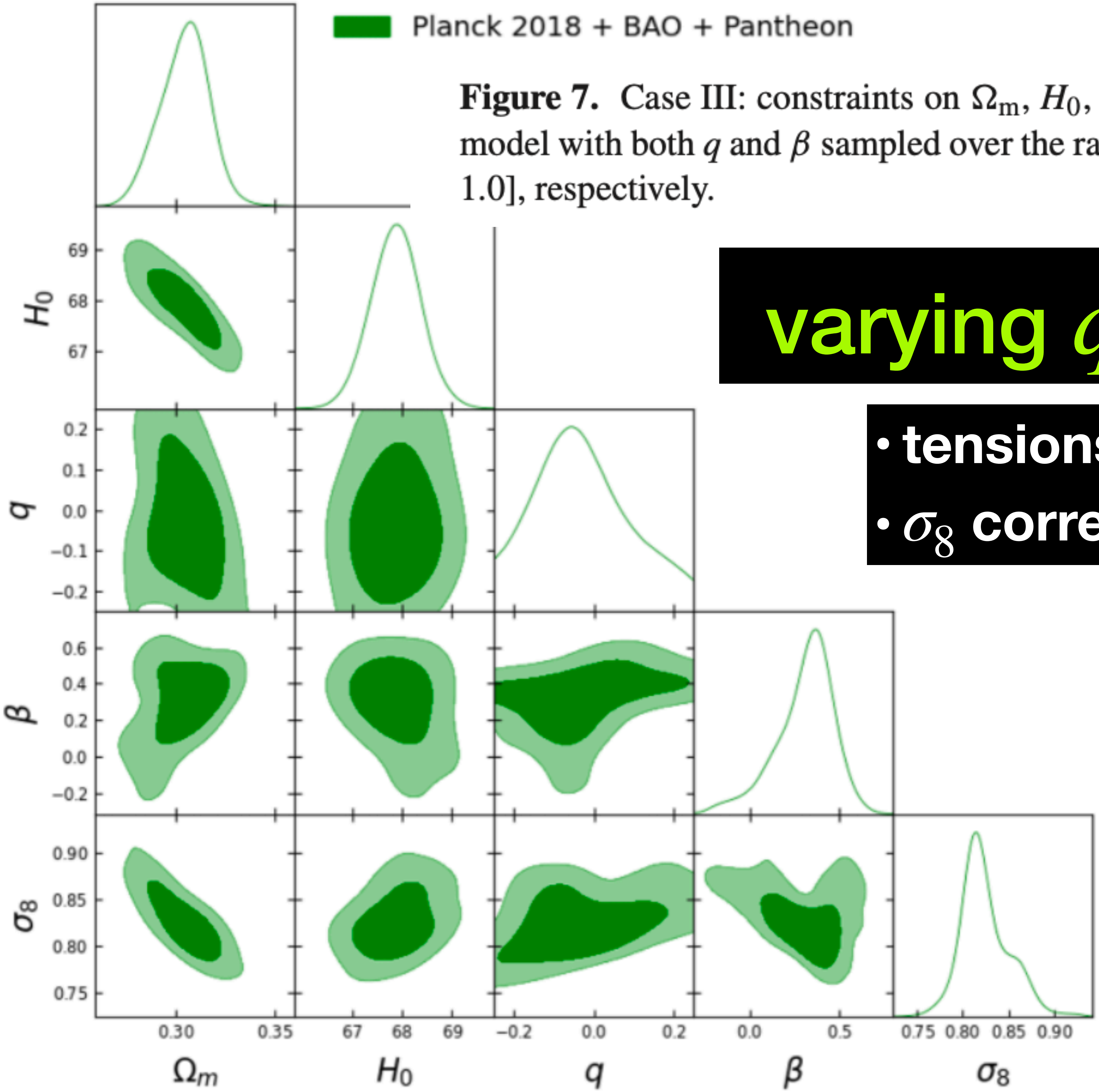


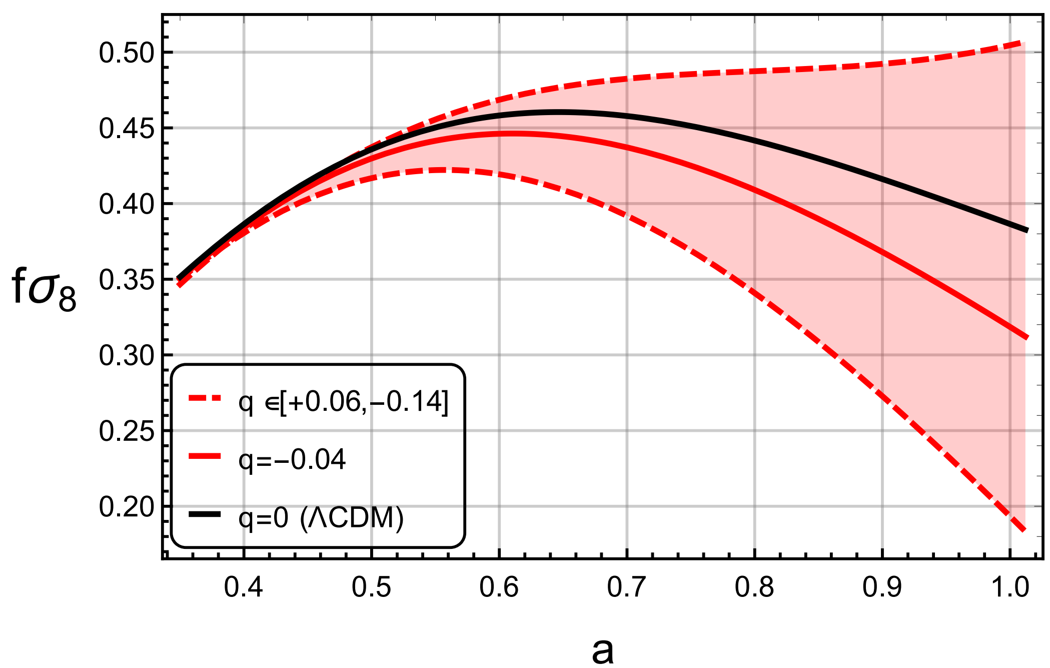
Figure 7. Case III: constraints on Ω_m, H_0, q, β, and σ_8 for the Shan–Chen model with both q and β sampled over the ranges $[-0.25, 0.25]$ and $[-1.0, 1.0]$, respectively.

varying q and β

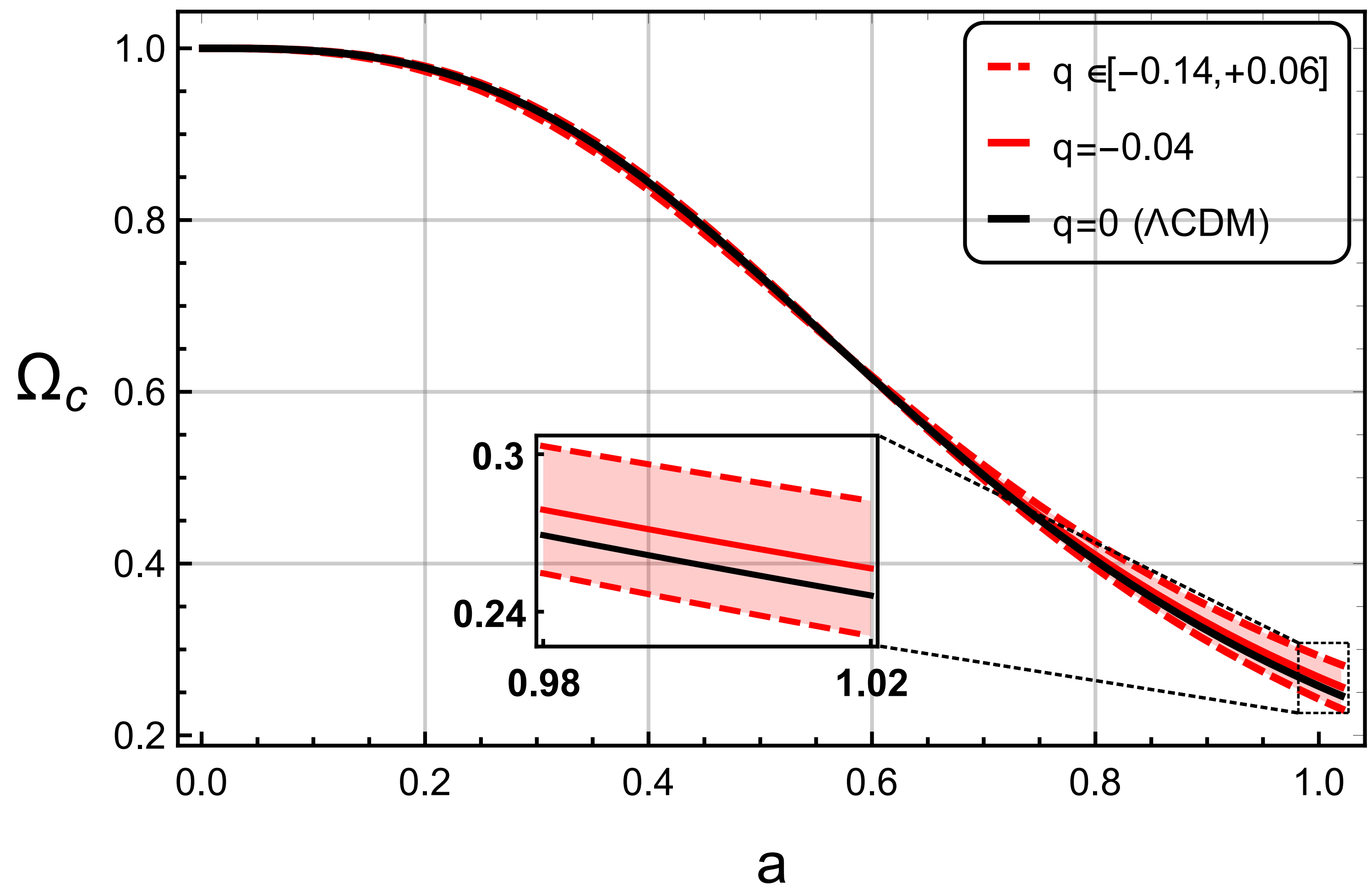
- tensions are stil there
- σ_8 correlates with H_0

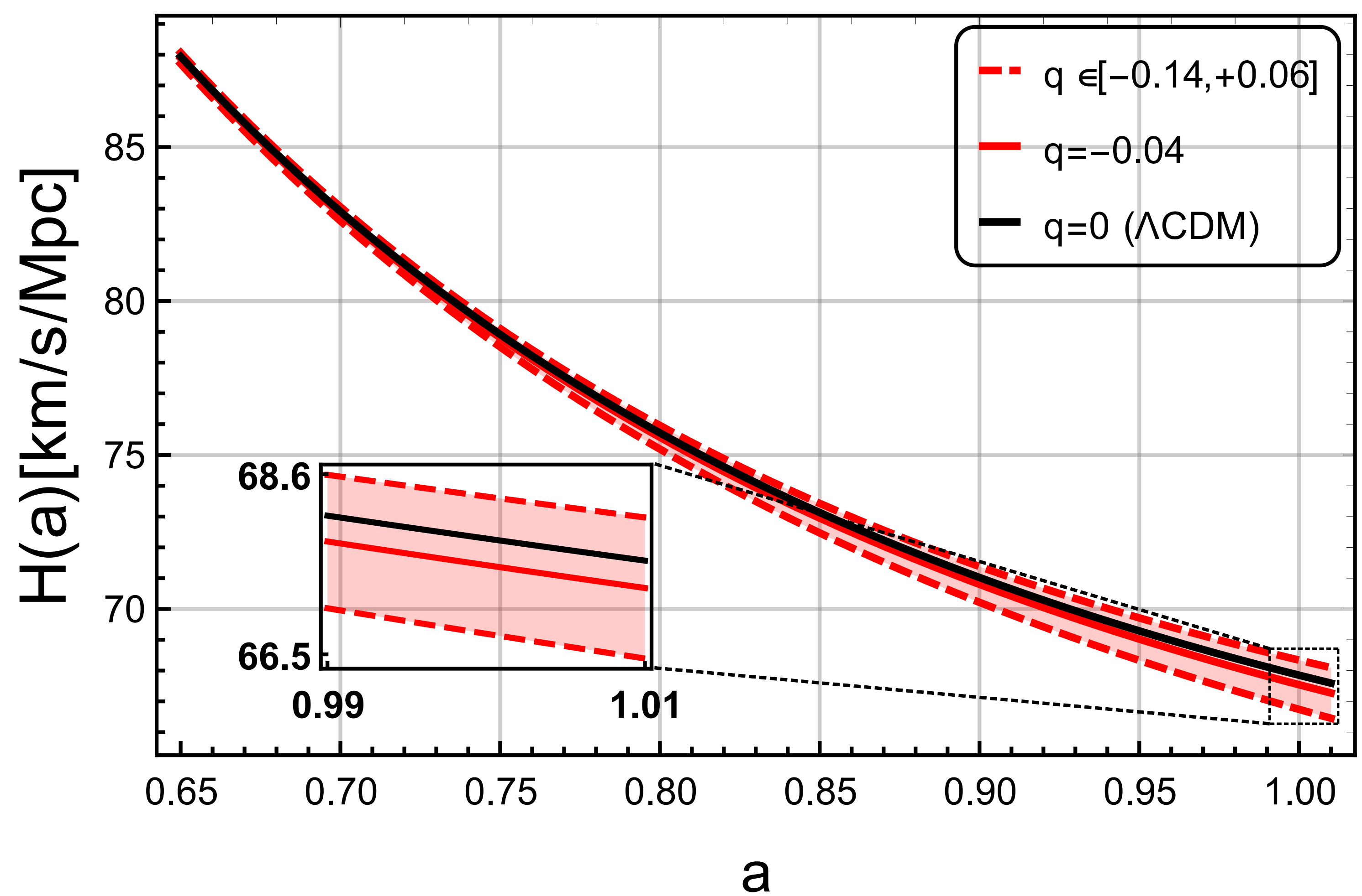
work with Marco Sebastianutti on Martinelli, Hogg, Peirone, MB & Wands 1902.10694,

cf Wands & Borges1709.08933

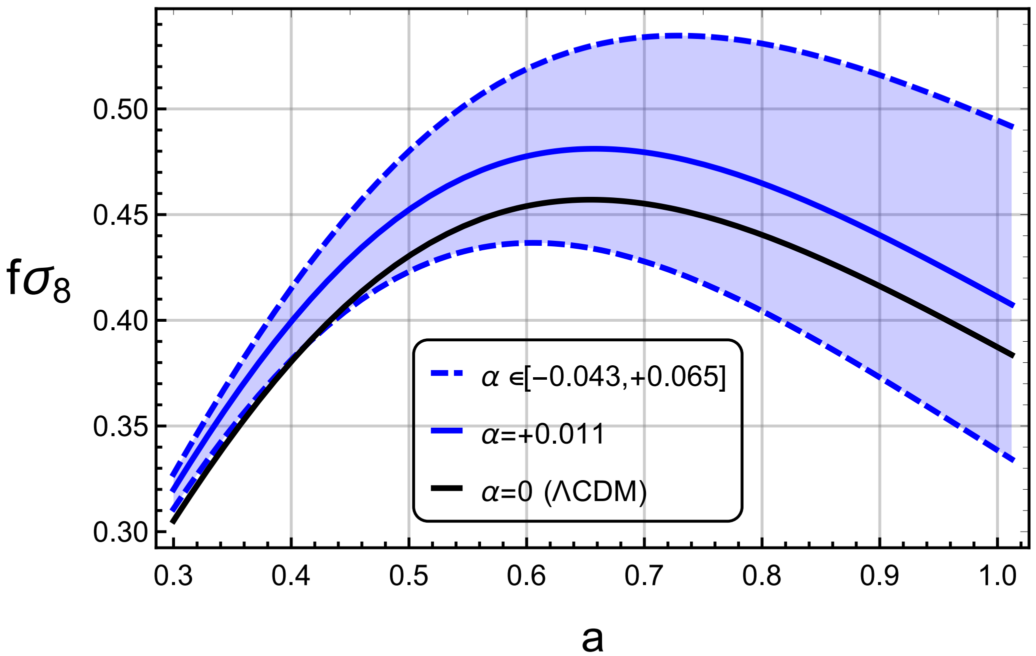


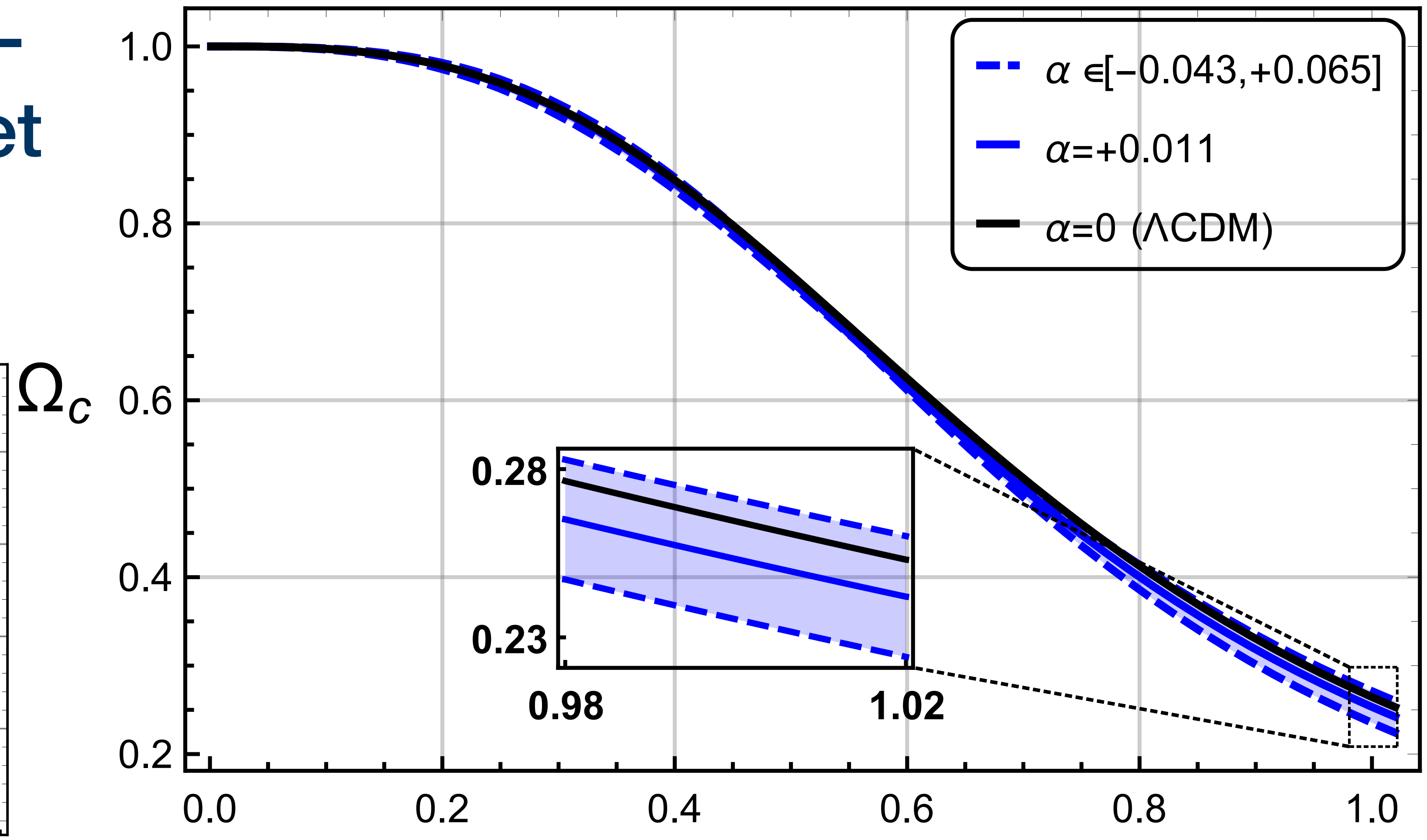
- LCDM vs best-fit interacting model, plus interacting models at $\pm 1\sigma$
- growing vacuum results in lower Ω_c and higher H_0, but $f\sigma_8$ is also higher

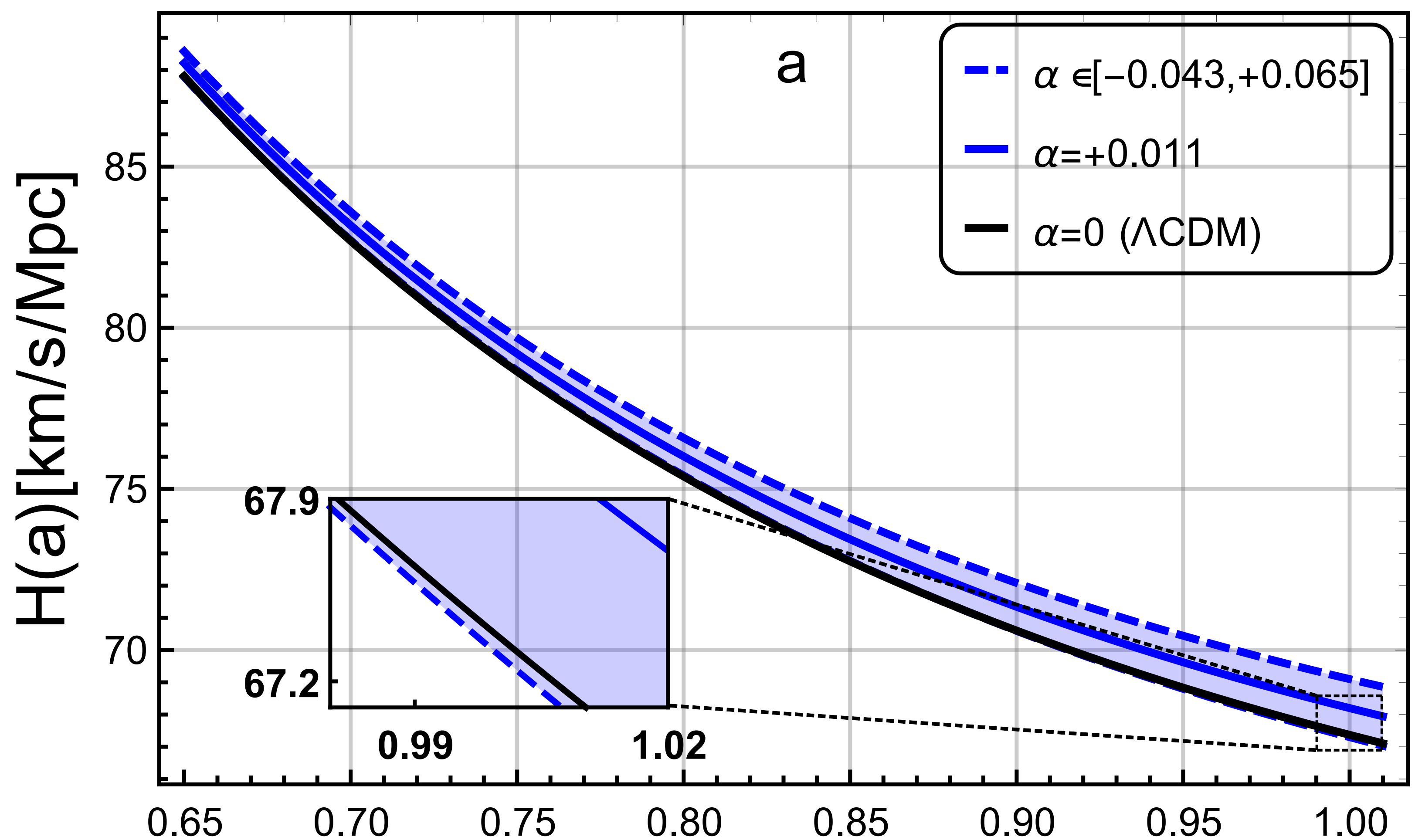




generalised Chaplygin-like interaction, Wang et al arXiv:1404.5706







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Final remarks

- numerical relativity cosmological simulations are in their infancy, but they are here to stay, hopefully contributing to improve our understanding of the Universe
- curvature doesn't have to be zero, but what it is that we actually measure as Ω_k ? see Tian et al 2010.07274 and Anselmi et al 2207.06547
- curvature could actually growth due to nonlinearity of Einstein equations: more work needed
- the Interacting Vacuum (IV) scenario offers interesting possibilities, but so far no much improvement on tensions
- typically, in the IV geodesic cases explored so far σ_8 correlates with H_0
- The Shan-Chen equation of state and its IV counterpart have a reach parameter space that is worth exploring further, especially for cases where $w_{int} < -1$

Tensions

Max Planck said that ***science advances one funeral at a time***. Or more precisely:

"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

I wish a long life to everybody involved, especially the older ones, also because I, like you, wish to see a solution: see you at next Tensions meeting!