

Void Radial Velocity Statistics as a Probe of Dark-Sector Interactions

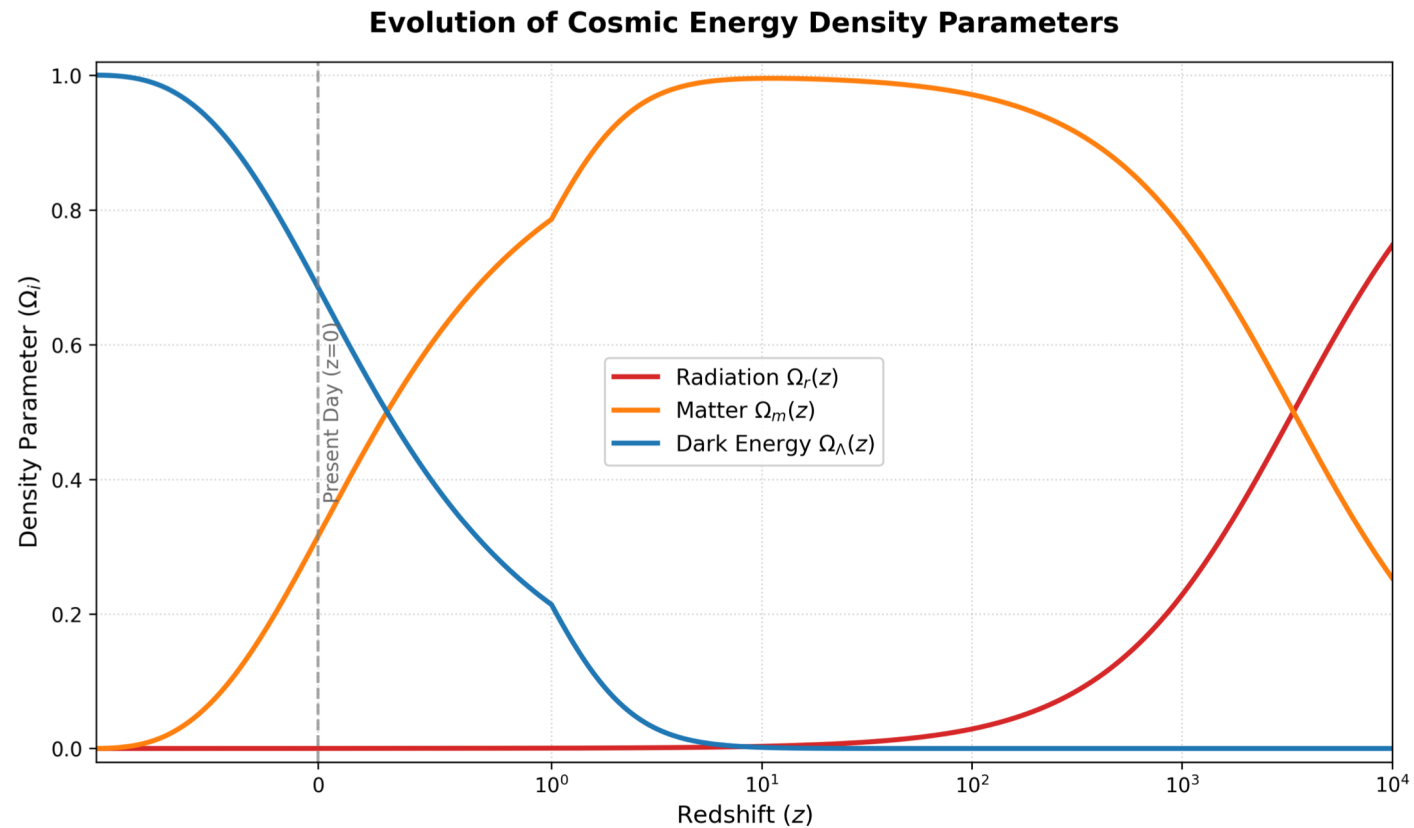
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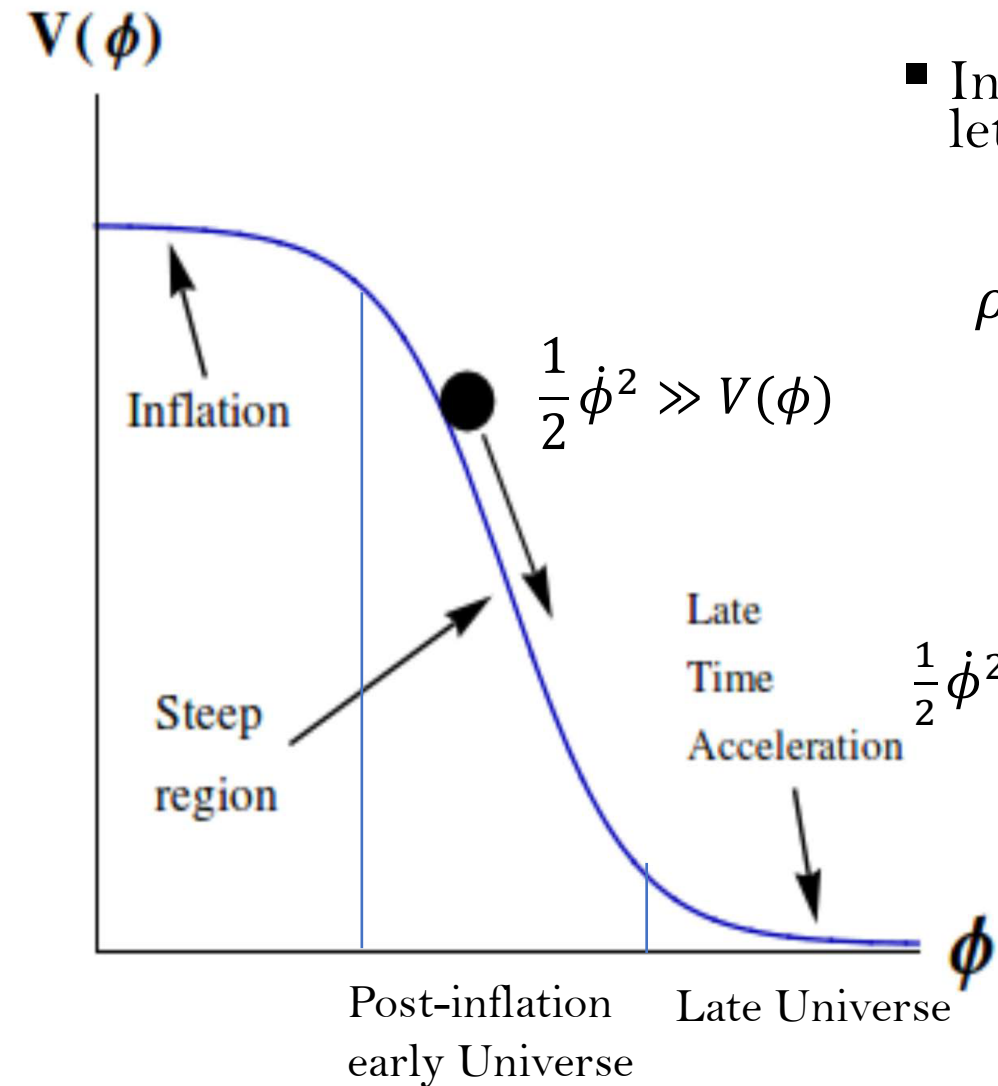


Introduction

- In Λ CDM, dark energy (DE) and dark matter (DM) evolves independently, yet their energy densities at $z = 0$ are of the same order, this is called the **cosmic coincidence**



Introduction: Alternatives to Λ CDM



- Instead of describing DE using a cosmological constant Λ , let's recast it as a varying scalar field ϕ

$$\rho_\phi = \underbrace{\frac{1}{2}\dot{\phi}^2}_{\text{Kinetic term}} + \underbrace{V(\phi)}_{\text{Potential term}}, \quad P_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi), \quad w_\phi = \frac{P_\phi}{\rho_\phi}$$

$$\frac{1}{2}\dot{\phi}^2 \ll V(\phi) \text{ (Slow rolling)}$$

$$w_\phi \approx -1$$

- Mimics the DE EoS of the Λ CDM ($\omega_{DE} = -1$)

Type 3 model

- Consider the **Type 3** model (Pourtsidou et al.), which describes DE as a scalar field and incorporates pure momentum exchange within the dark sector (DM and DE)
- A quintessence scalar field ϕ with momentum coupling β and potential slope λ .

Interaction term

$$L_\phi = -\frac{1}{2}(g^{\mu\nu} + \overbrace{2\beta u^\mu u^\nu}) \nabla_\mu \phi \nabla_\nu \phi - V(\phi)$$

$u^\mu = (1,0,0,0)$ (DM four velocity)

$$L_\phi = \underbrace{\frac{1}{2}(1 - 2\beta)\dot{\phi}^2}_{\text{Kinetic term}} - \underbrace{\frac{1}{2}|\vec{\nabla}\phi|^2}_{\text{Spatial term (= 0)}} - \underbrace{V(\phi)}_{\text{Potential term} = V_0 e^{-\frac{\lambda\phi}{m_P}}}$$

$$\nabla_\mu T^{(c)\mu}_\nu = -\nabla_\mu T^{(DE)\mu}_\nu = J_\nu \approx 0$$

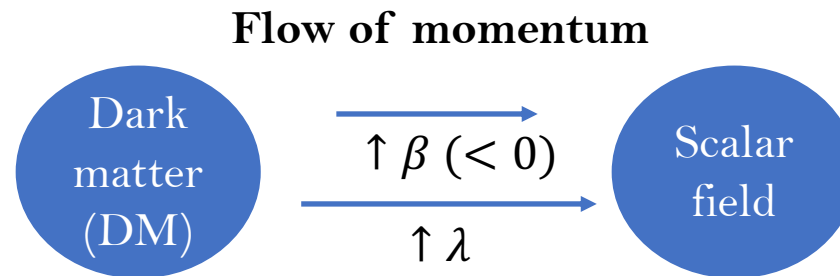
- Momentum transfer exists between the dark sector, but no energy transfer $\rightarrow$ background evolution of the energy densities is uncoupled.

Type 3 model

$$L_\phi = \underbrace{\frac{1}{2}(1 - 2\beta)\dot{\phi}^2}_{\text{Kinetic term}} - \underbrace{\frac{1}{2}|\vec{\nabla}\phi|^2}_{\text{Spatial term (= 0)}} - \underbrace{V(\phi)}_{\text{Potential term} = V_0 e^{-\frac{\lambda\phi}{m_P}}}$$

■ Effects of β and λ :

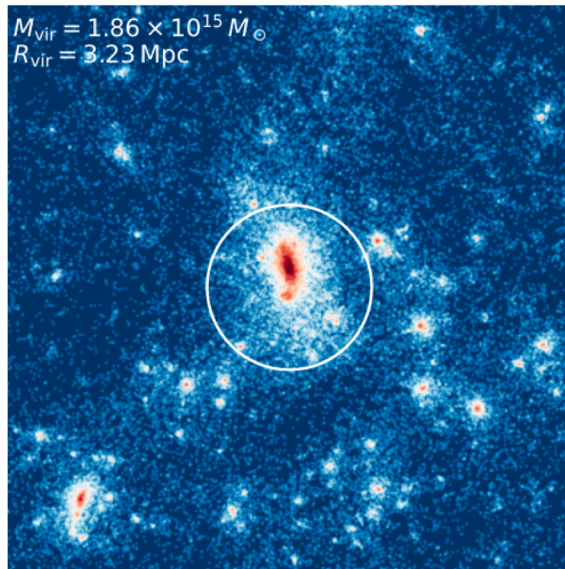
- $\beta < 0$: In term $-\beta\dot{\phi}^2$, when β approaches 0, the kinetic term decreases
- λ : In term $\frac{1}{2}(1 - 2\beta)\dot{\phi}^2$, increase in λ speeds up the scalar field evolution $\dot{\phi}$ to increase the kinetic term



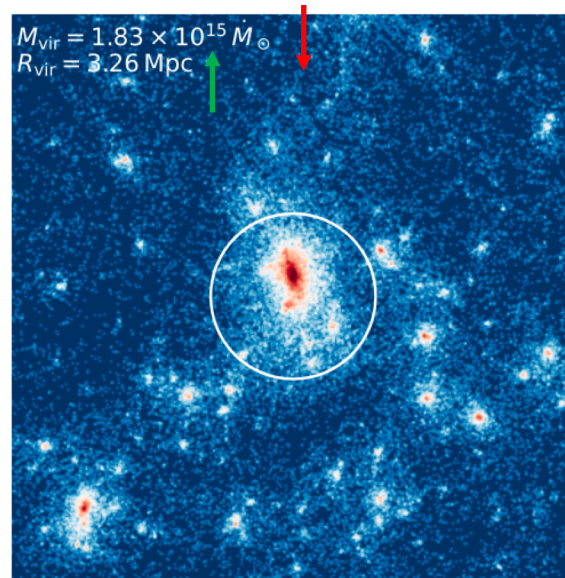
Type 3 model: effects on dark matter halos

- Dark sector interaction affects structure formation of halos and momentum transfer, suggesting that it also affects halos motion

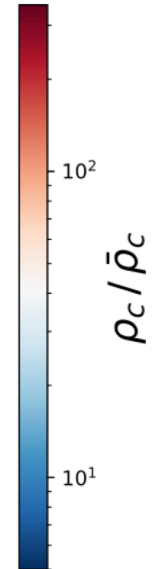
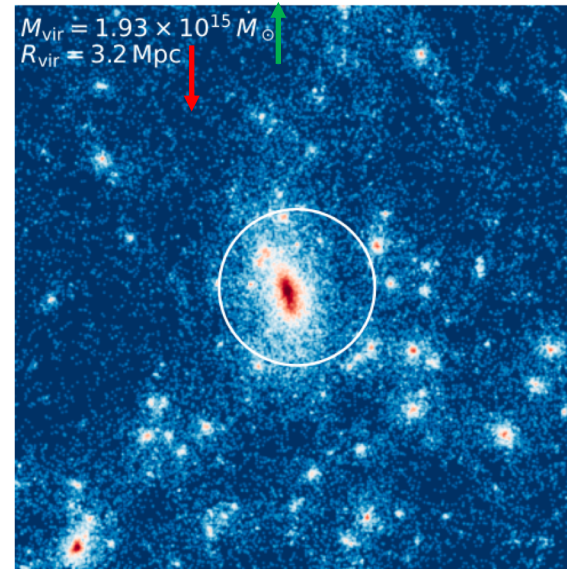
$$\beta = -1.4, \lambda = 0.6$$



$$\beta = -0.5, \lambda = 0.6$$



$$\beta = -0.5, \lambda = 1.4$$



$20 \times 20 \times 60 \text{ Mpc}^3 h^{-3}$

Cosmic voids as cosmological laboratories

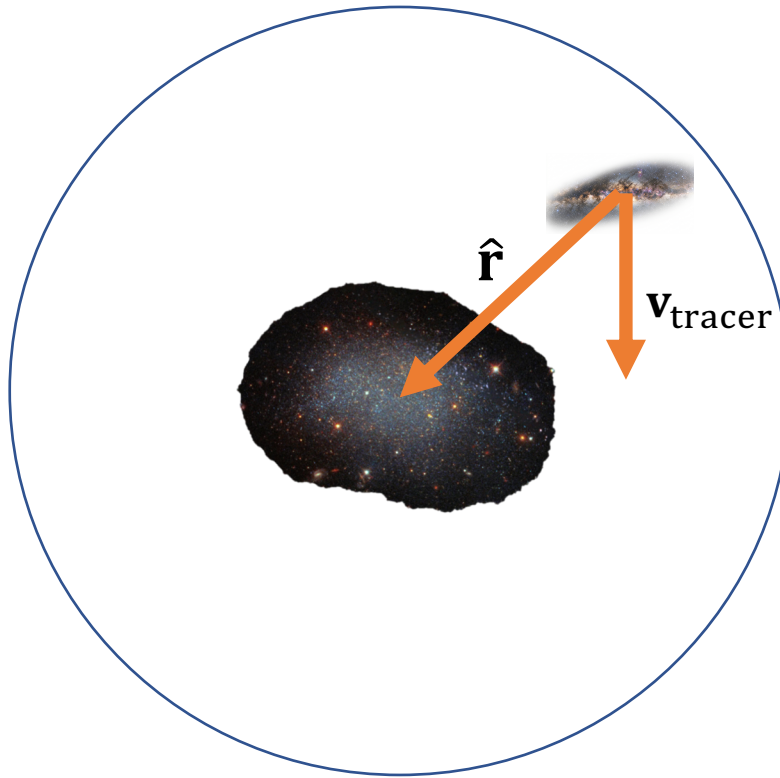
- Cosmic Voids
 - Under-dense regions minimally affected by baryonic processes
 - Continuously expanding (similar to a mini-universe) and occupy huge volume
 - Ideal for testing gravity and dark energy models, and studying tracer's kinematics around voids can probe dark sector interactions



Credit: ESO/NASA

Void radial velocity statistics

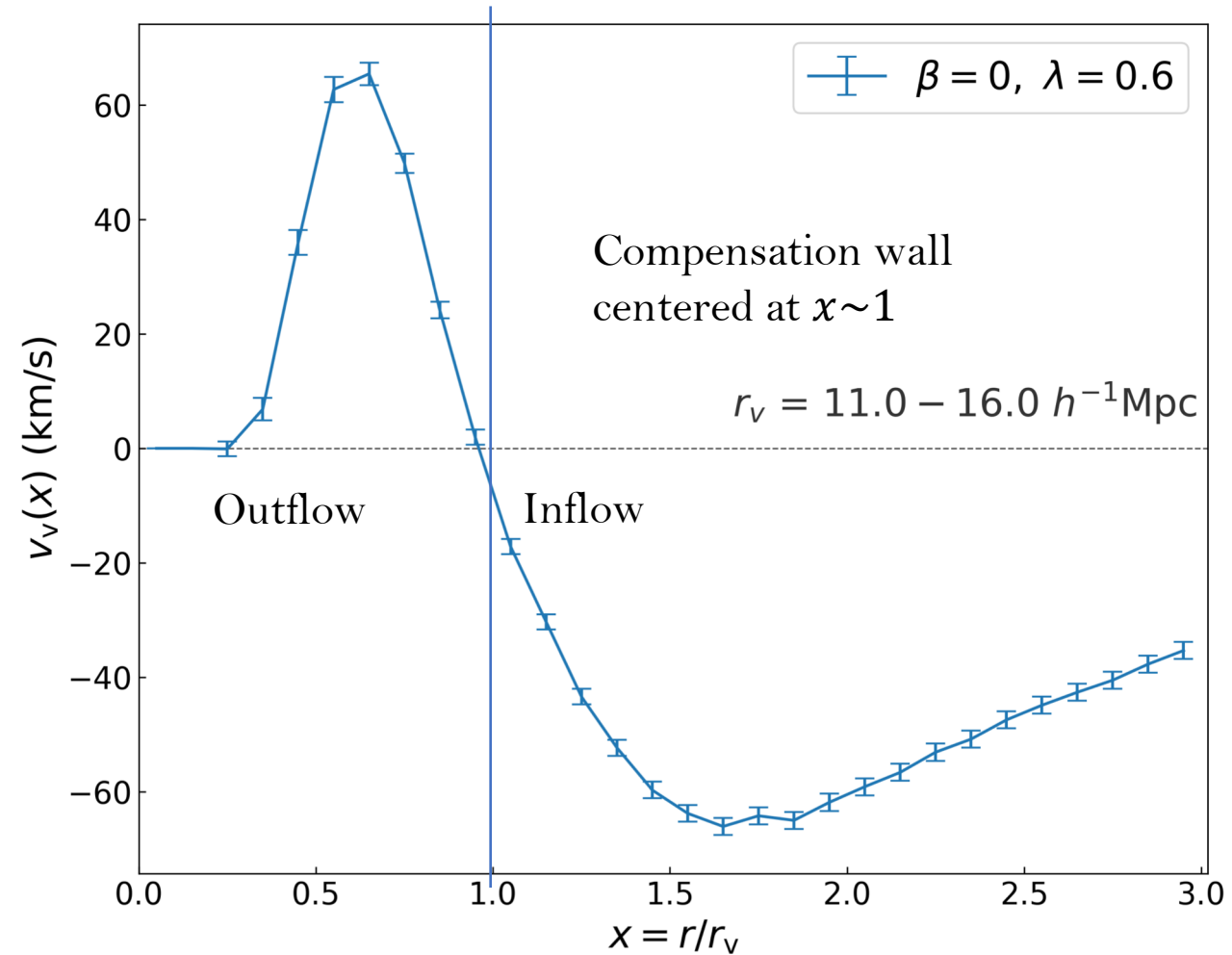
- **Radial Velocity Profile v_v** : Radial velocity profile measures mean peculiar velocity of tracers from void centre



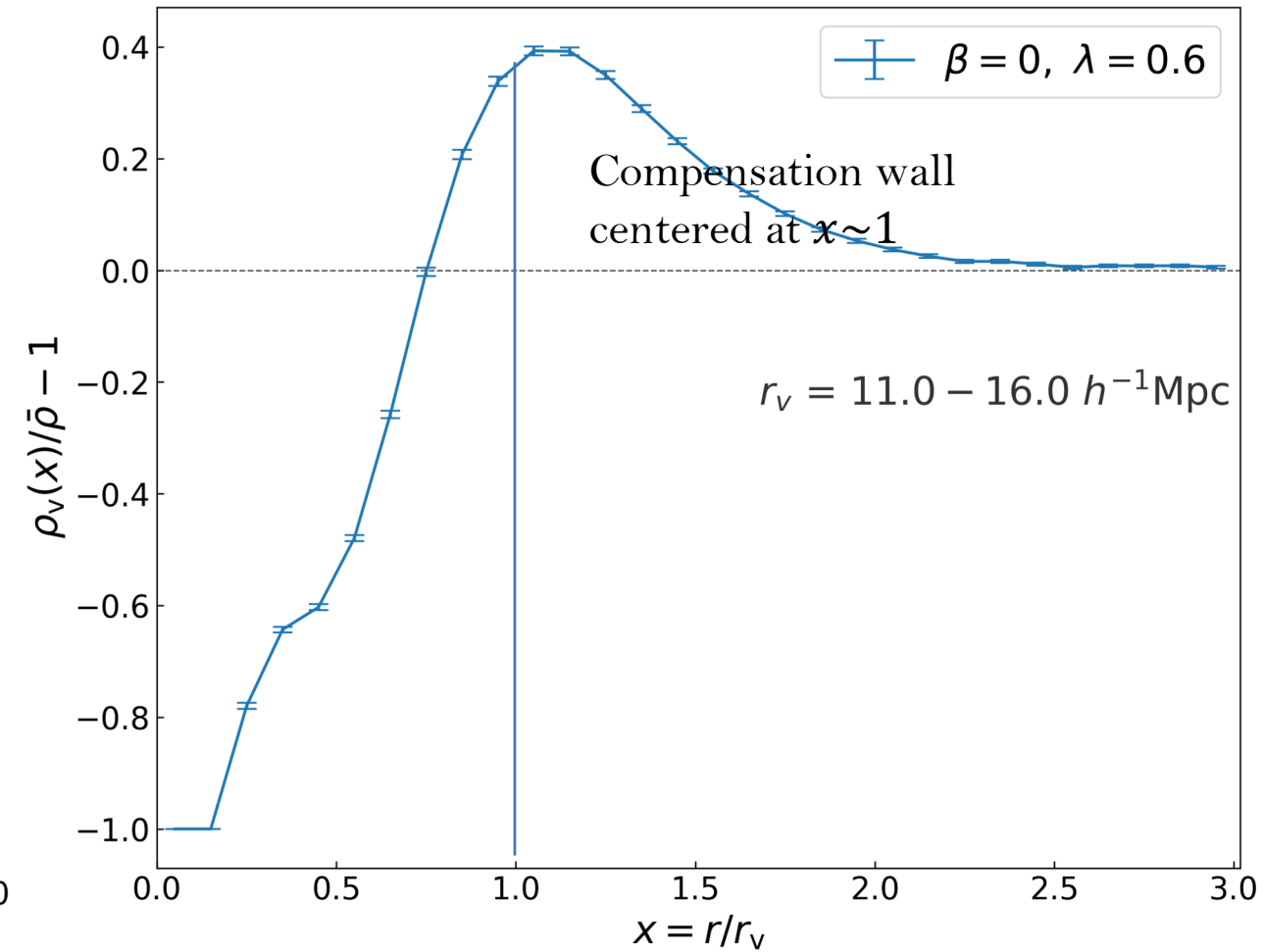
- **Velocity Dispersion Profile σ_v** : Velocity dispersion profile quantifies spread of tracer velocities around voids

Void radial velocity statistics

Void radial velocity profile v_v



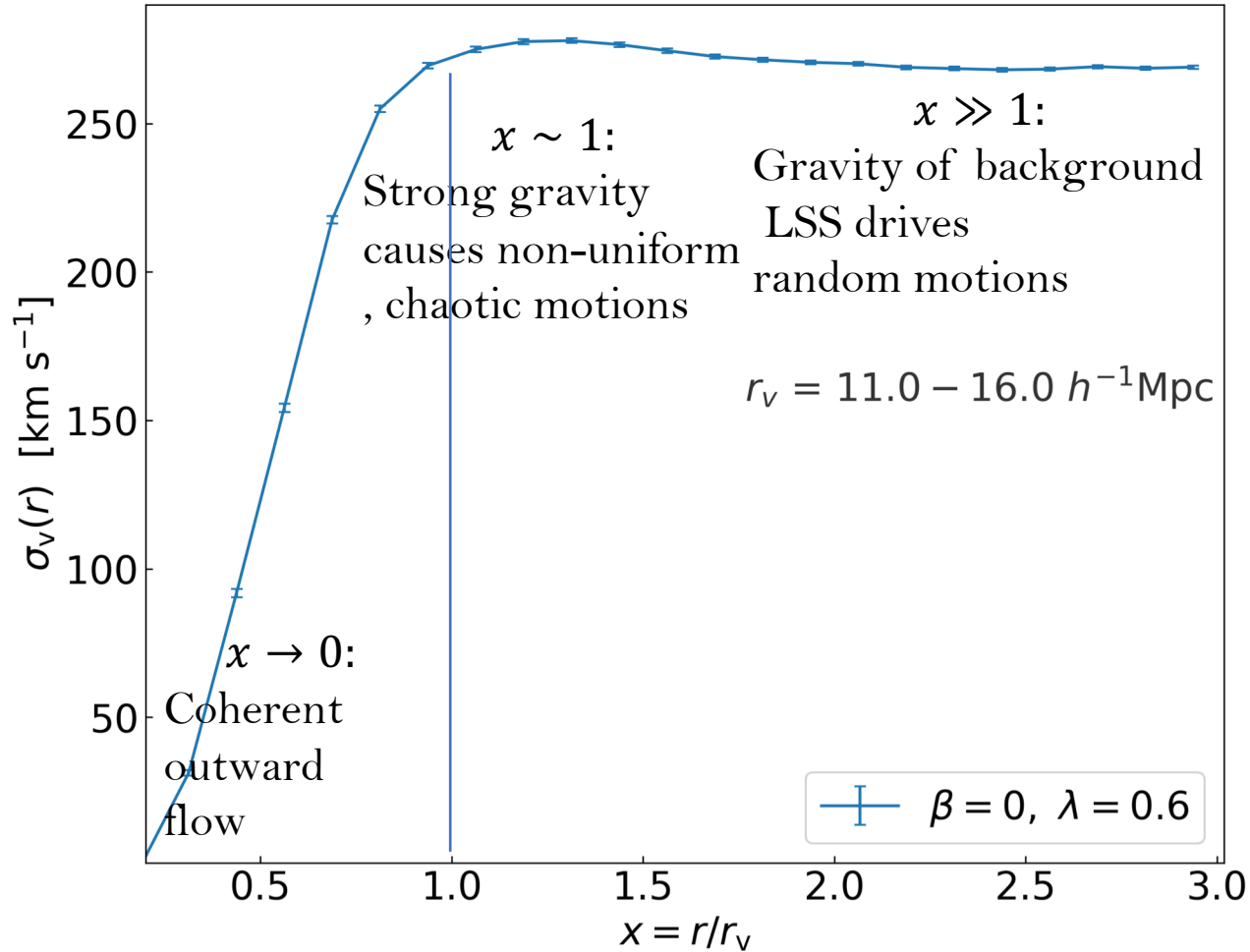
Void density profile δ_v



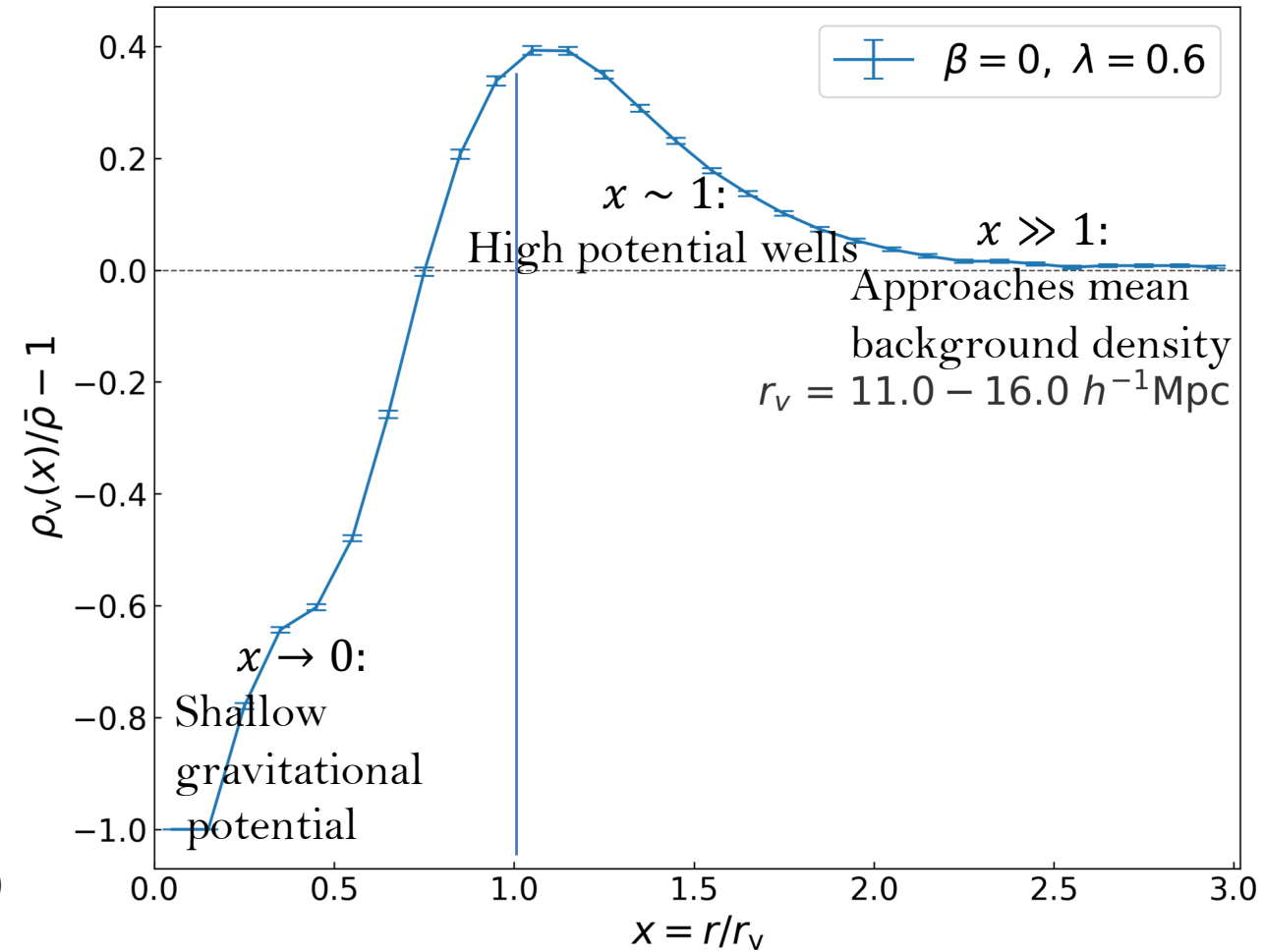
Void radial velocity statistics

Virial Theorem:
 $\langle T \rangle = -2\langle V \rangle$

Void radial velocity dispersion profile σ_v



Void density profile δ_v



Methodology

1. CLASS (Linear perturbation solver modified for the Type 3 model)
Accurately describes the Type 3 model at linear scales because it has no energy transfer (evolution of energy densities is uncoupled)

2. Cobaya (Monte Carlo code for cosmological parameter extraction)
Pick 3 values of β and λ ($3 \times 3 = 9$ cases), and fiducial case ($\beta = 0, \lambda = 0.6$)

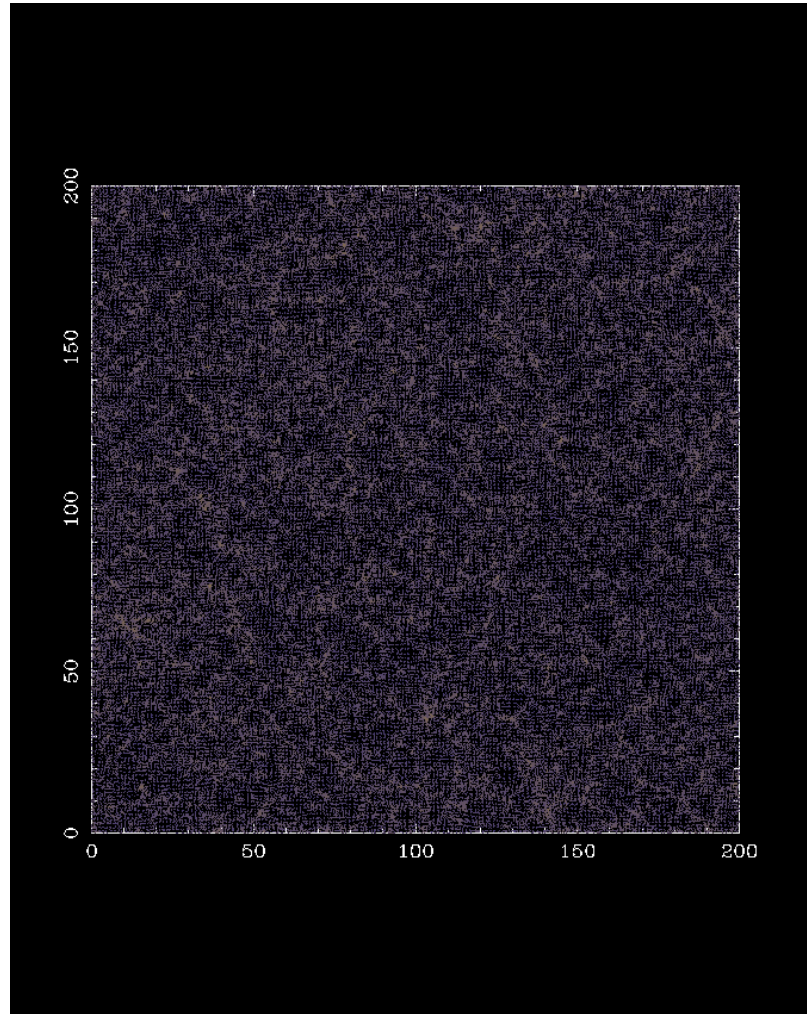
For all cases, re-fit the cosmological parameters to observational datasets (Planck CMB, DESI DR2, DES-Y5) and do

3. 2LPTic (Initial condition generator, $z = 49$)

4. ME-Gadget-2 (N -body simulation code, 1024^3 DM particles)

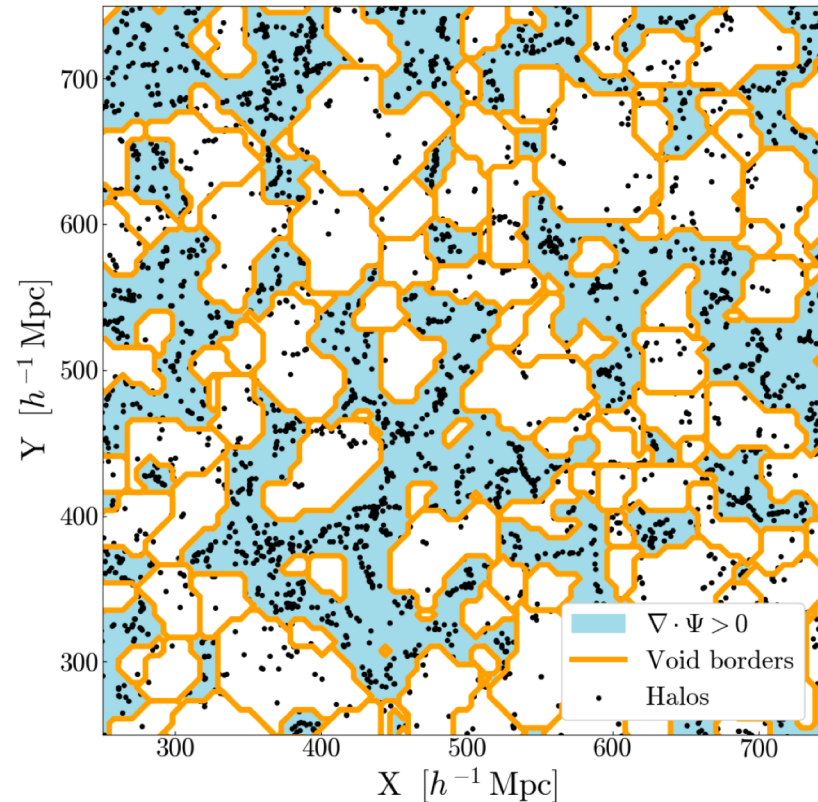
Methodology (N-body simulations)

4. ME-Gadget-2 (N -body simulation code, 1024^3 DM particles)



Methodology

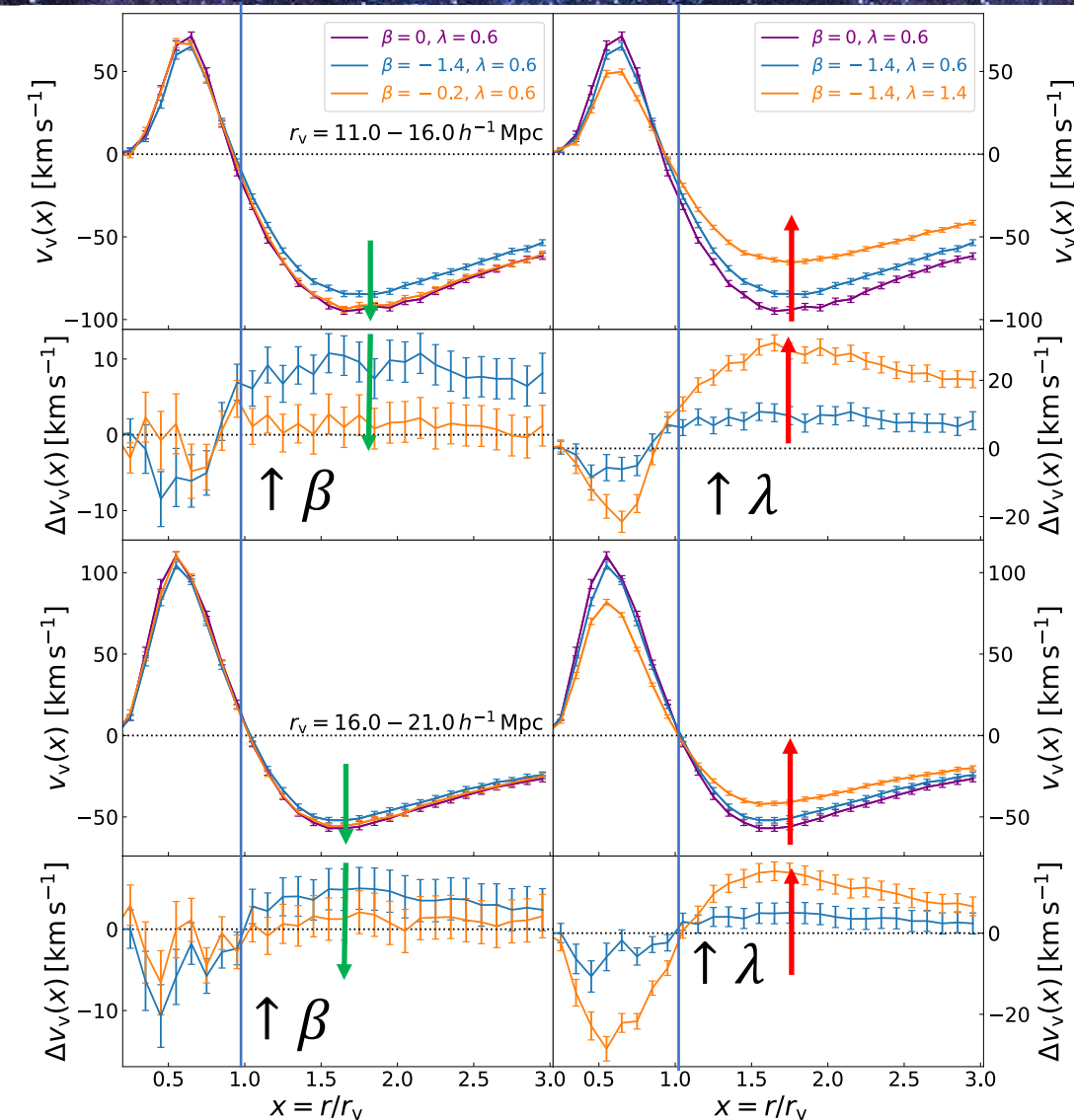
5. ROCKSTAR (Dark matter halo finder) + VIDE (Void finder) at $z = 0$



Credit: Simone Sartori

6. Self developed codes (Void radial velocity statistics calculator)
- 1) Sampled voids in different sizes ($r_v = 11 - 16 h^{-1} \text{Mpc}$, $r_v = 16 - 21 h^{-1} \text{Mpc}$)

Results (Halo): Void radial velocity profile v_v

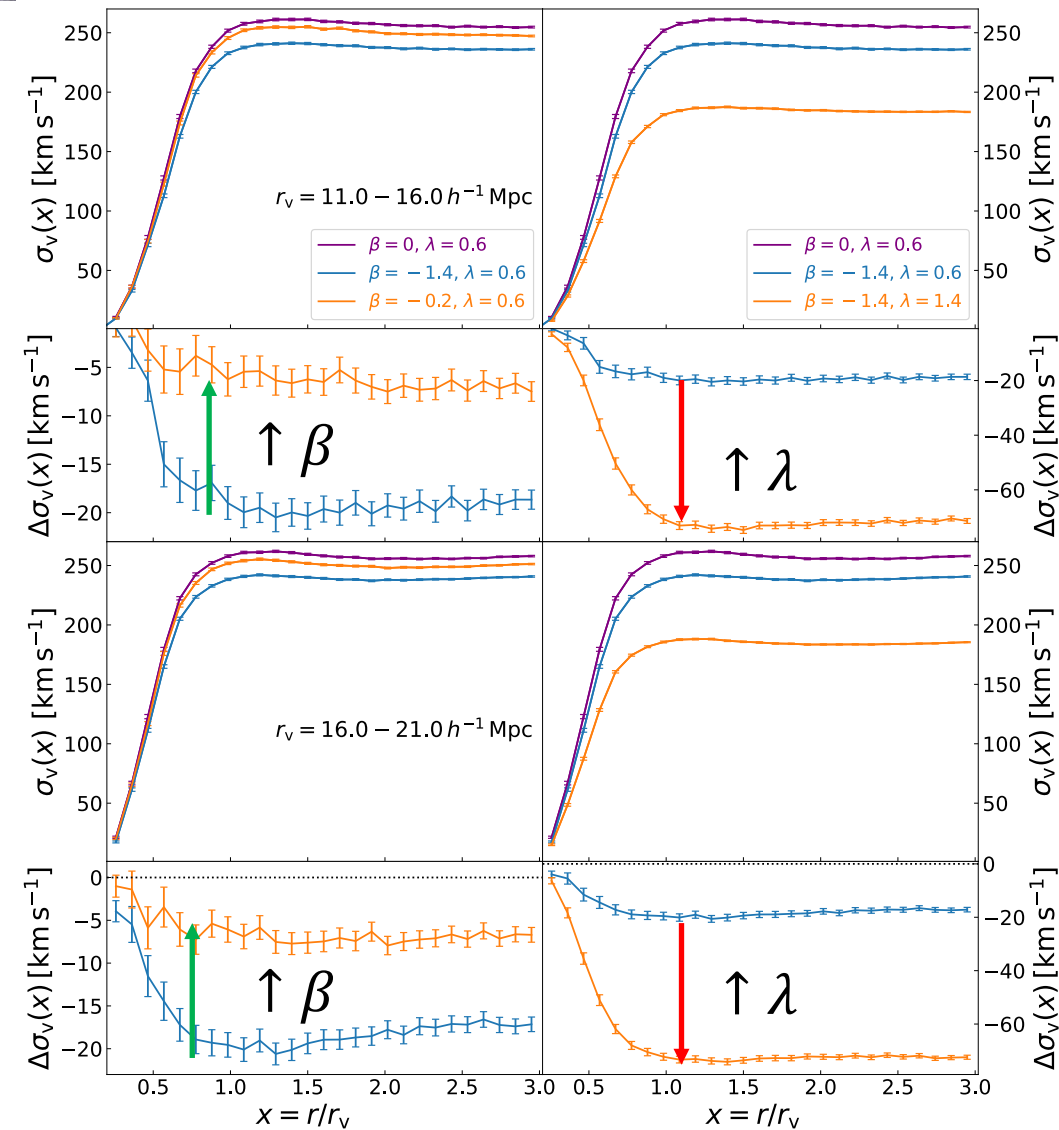


v_v : $\beta(< 0)$

- At all x observed, as β approaches 0 (weaker coupling), it increases the velocity magnitude because less momentum is lost to the scalar field, so halos experience less friction to overall motions
- While for larger λ (steeper slope), the magnitude decreases, because the moving halos lose more momentum to scalar field, and their motions become more dampened.

$$L_\phi = \underbrace{\frac{1}{2}(1 - 2\beta)\dot{\phi}^2}_{\text{Kinetic term}} - \underbrace{\frac{1}{2}|\vec{\nabla}\phi|^2}_{\text{Spatial term (=0)}} - \underbrace{V(\phi)}_{\text{Potential term}} \quad (3)$$

Results (Halo): Void radial dispersion velocity σ_v

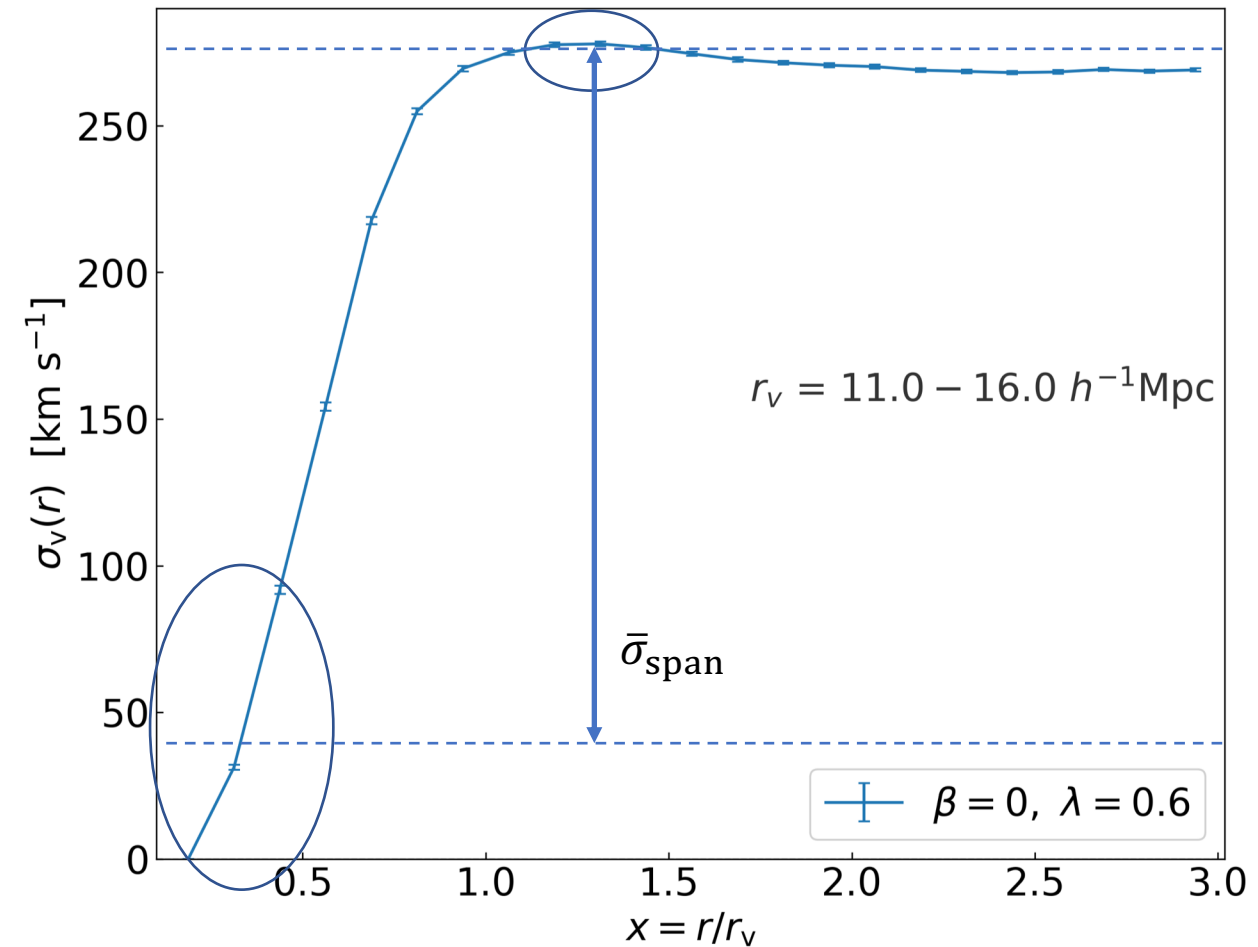
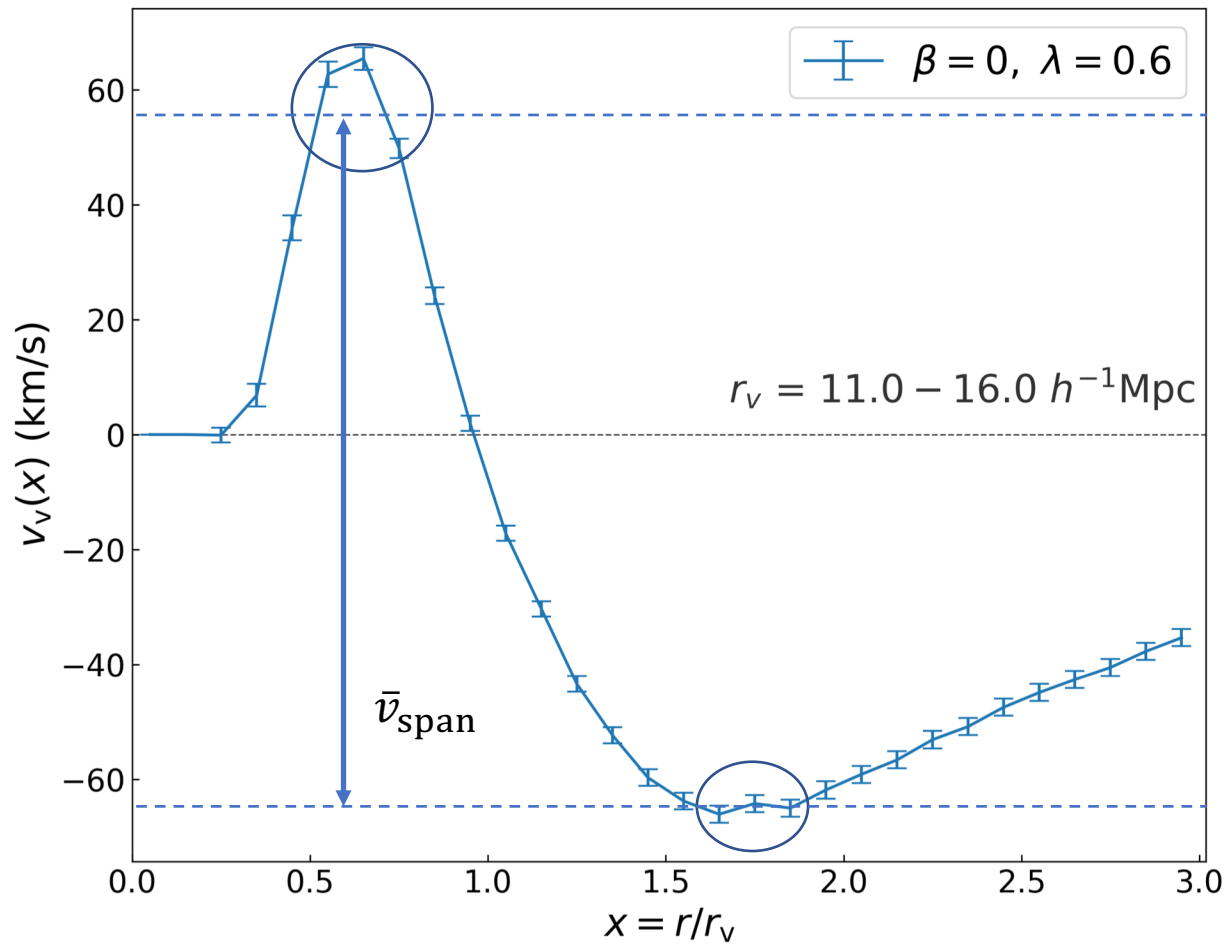


σ_v : $\beta(< 0)$

■ The same can be said for σ_v

$$L_\phi = \underbrace{\frac{1}{2}(1 - 2\beta)\dot{\phi}^2}_{\text{Kinetic term}} - \underbrace{\frac{1}{2}|\vec{\nabla}\phi|^2}_{\text{Spatial term (=0)}} - \underbrace{V(\phi)}_{\text{Potential term}} \quad (3)$$

Velocity spans and 4-variable regression



Velocity spans and 4-variable regression

- Calculate the fractional deviation of $\bar{v}_{\text{span}}$ and $\bar{\sigma}_{\text{span}}$ of all scenarios relative to the uncoupled ($\beta = 0, \lambda = 0.6$) fiducial scenario and fit to a 4-variable regression

$$\Delta[\bar{v}_{\text{span}} | \bar{\sigma}_{\text{span}}] = c_{\beta}\Delta\beta + c_{\lambda}\Delta\lambda + c_{\beta\beta}\Delta\beta^2 + c_{\beta\lambda}\Delta\beta\Delta\lambda, \quad \text{with } \Delta\beta = \beta + 1.4, \Delta\lambda = \lambda - 0.6$$

Quantity	$r_v [h^{-1}\text{Mpc}]$	c_{β} (%)	c_{λ} (%)	$c_{\beta\beta}$ (%)	$c_{\beta\lambda}$ (%)	R^2 ($\bar{R}^2$)
$\Delta\bar{v}_{\text{span}}$	11.0 – 16.0	14.51 ± 2.76	-11.34 ± 2.14	7.13 ± 2.13	11.16 ± 2.36	0.987 (0.980)
	16.0 – 21.0	18.41 ± 2.59	-9.41 ± 2.02	9.28 ± 2.00	13.11 ± 2.23	0.992 (0.988)
$\Delta\bar{\sigma}_{\text{span}}$	11.0 – 16.0	12.51 ± 1.19	-8.74 ± 0.92	6.39 ± 0.91	13.73 ± 1.02	0.996 (0.993)
	16.0 – 21.0	10.33 ± 1.84	-12.93 ± 1.41	4.78 ± 1.41	10.21 ± 1.57	0.990 (0.984)

- The significant cross-term $c_{\beta\lambda}$ is explained by the dark sector interaction, encoded in the term $-\beta\dot{\phi}^2$

Recall
$$L_{\phi} = \underbrace{\frac{1}{2}(1 - 2\beta)\dot{\phi}^2}_{\text{Kinetic term}} - \underbrace{\frac{1}{2}|\vec{\nabla}\phi|^2}_{\text{Spatial term (=0)}} - \underbrace{V(\phi)}_{\text{Potential term}} \quad (3)$$

Conclusion and Outlook

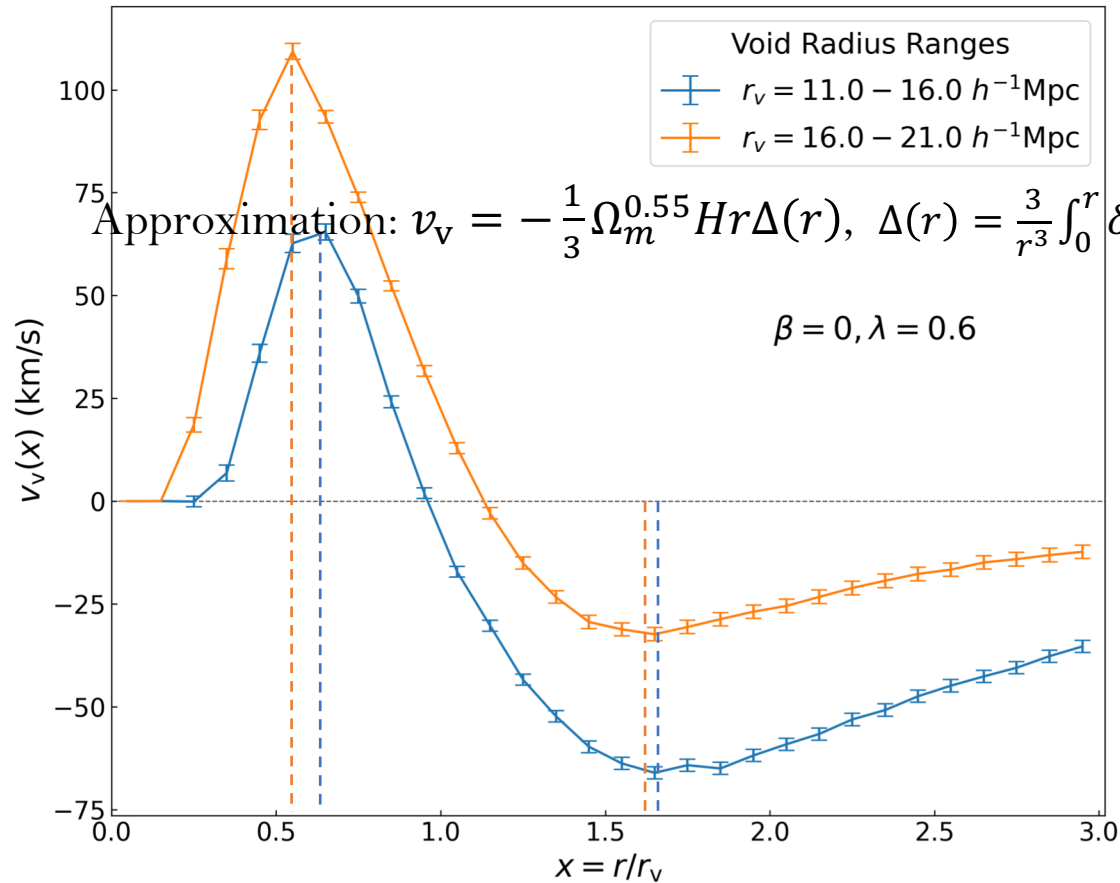
- β and λ induce opposing primary effects on the void radial velocity statistics, acting to increase and decrease the magnitudes, respectively
- The non-negligible cross co-efficient $c_{\beta\lambda}$ means that steeper potential slope (λ increases) increases the sensitivity of the velocity statistics to the momentum coupling
- In summary, the kinematics of tracers around voids effectively traces the effect of interacting dark energy.
- It will be meaningful to study net effect of the cosmic voids on the expansion of the universe, know as void back-reaction



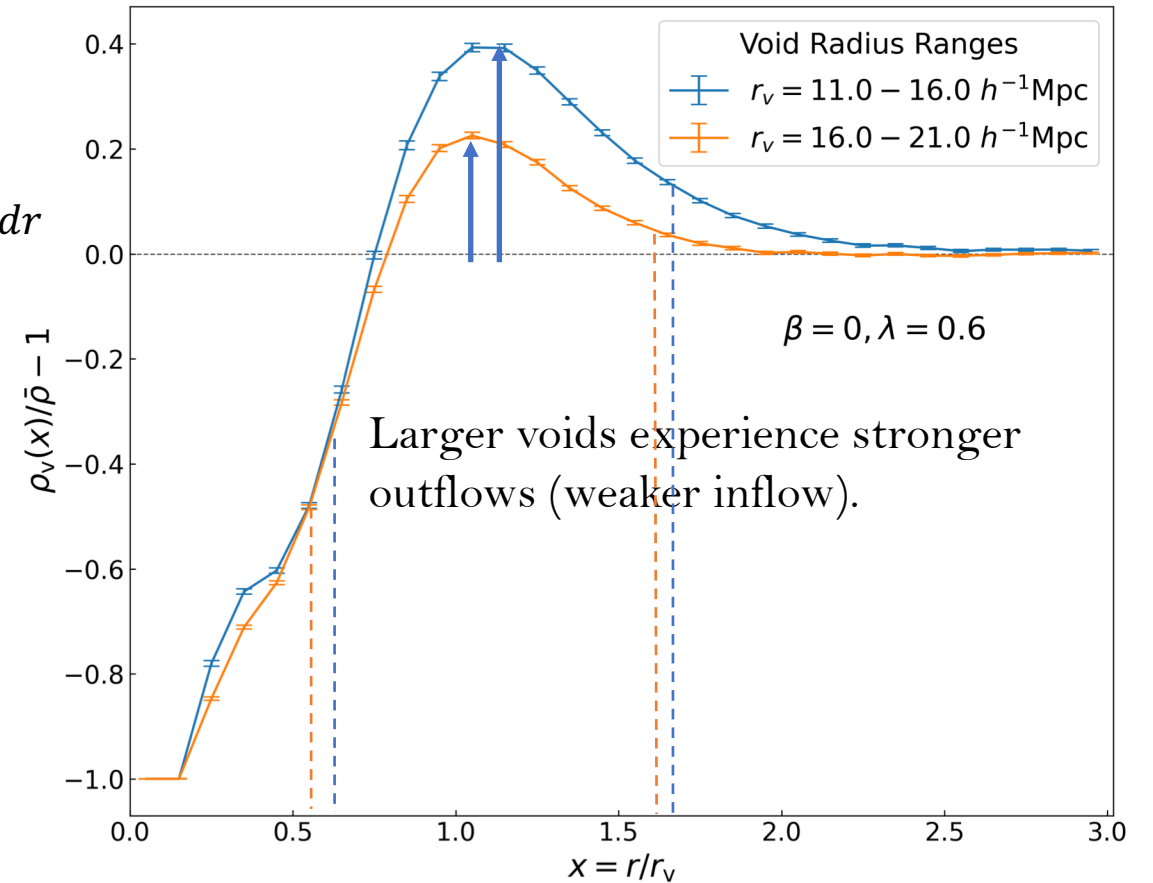
The end

Appendix: Void radial velocity statistics

Void Radial Velocity Profile v_v



Void Density Profile δ_v

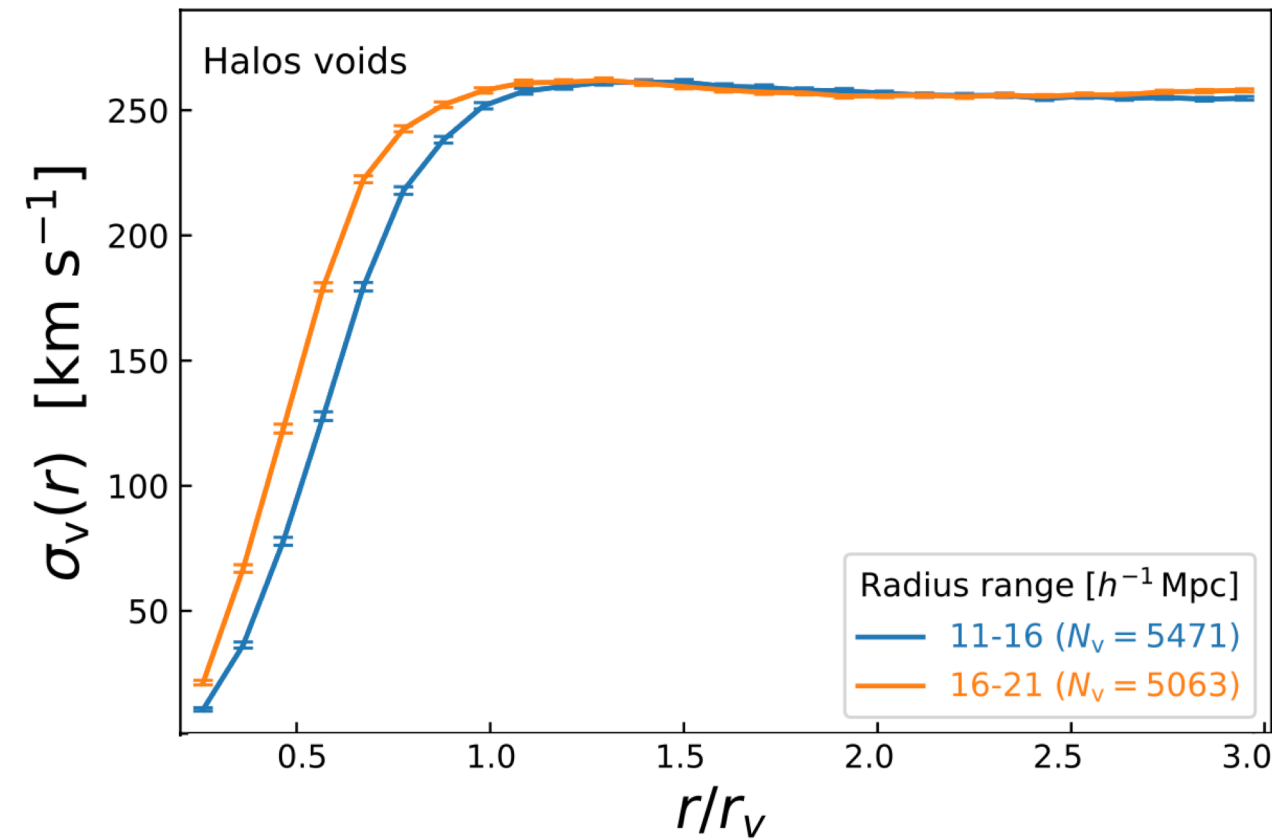


At $x < 1$, as $v_v \propto Hr \Delta(r)$ and the difference in mass deficit $\Delta(r)$, is little, so larger voids exhibit stronger outflows

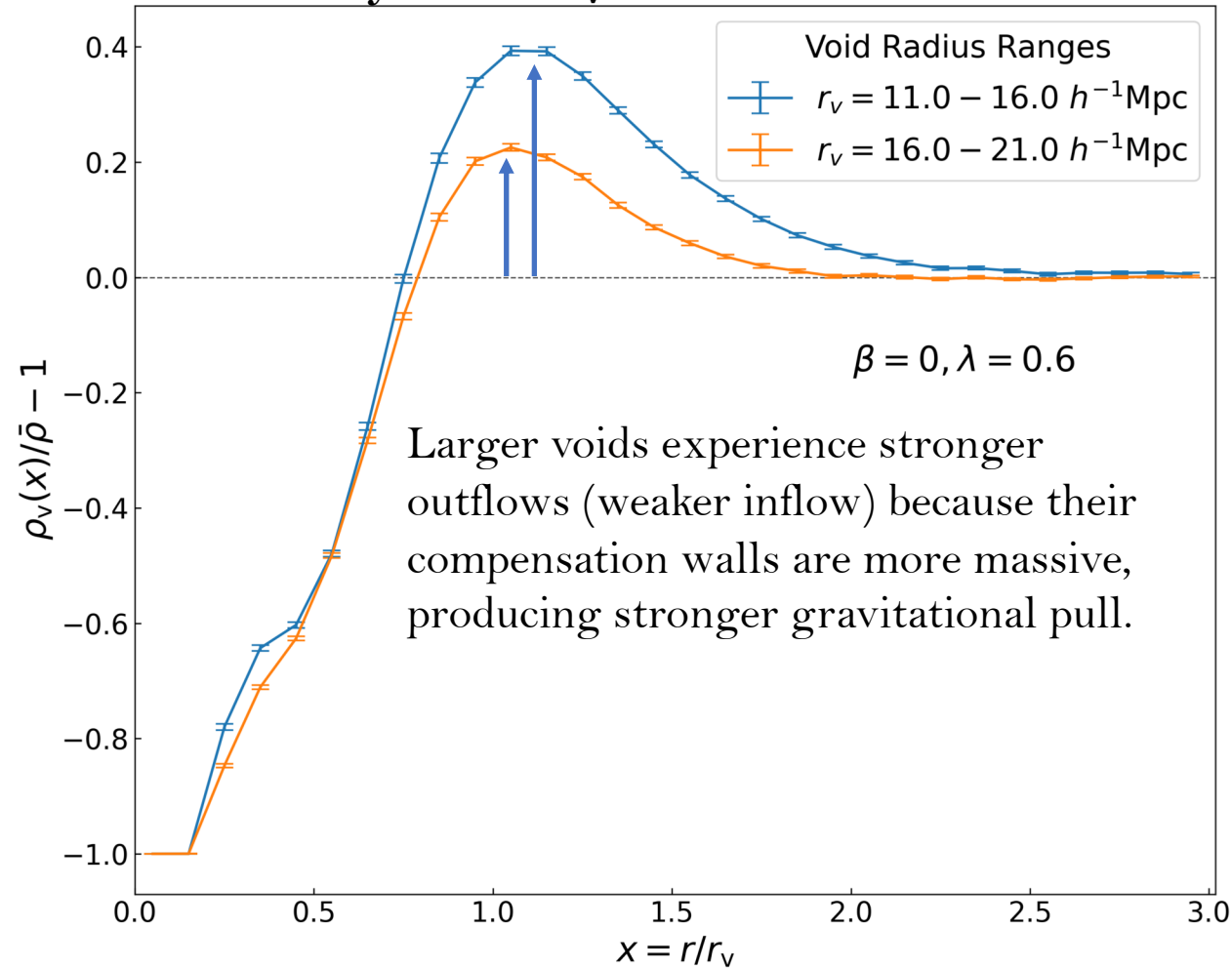
At $x > 1$, the difference in mass excess $\Delta(r)$ increases, with the smaller voids enclosing much more mass, so smaller voids exhibit stronger inflow.

Appendix: Void radial velocity statistics

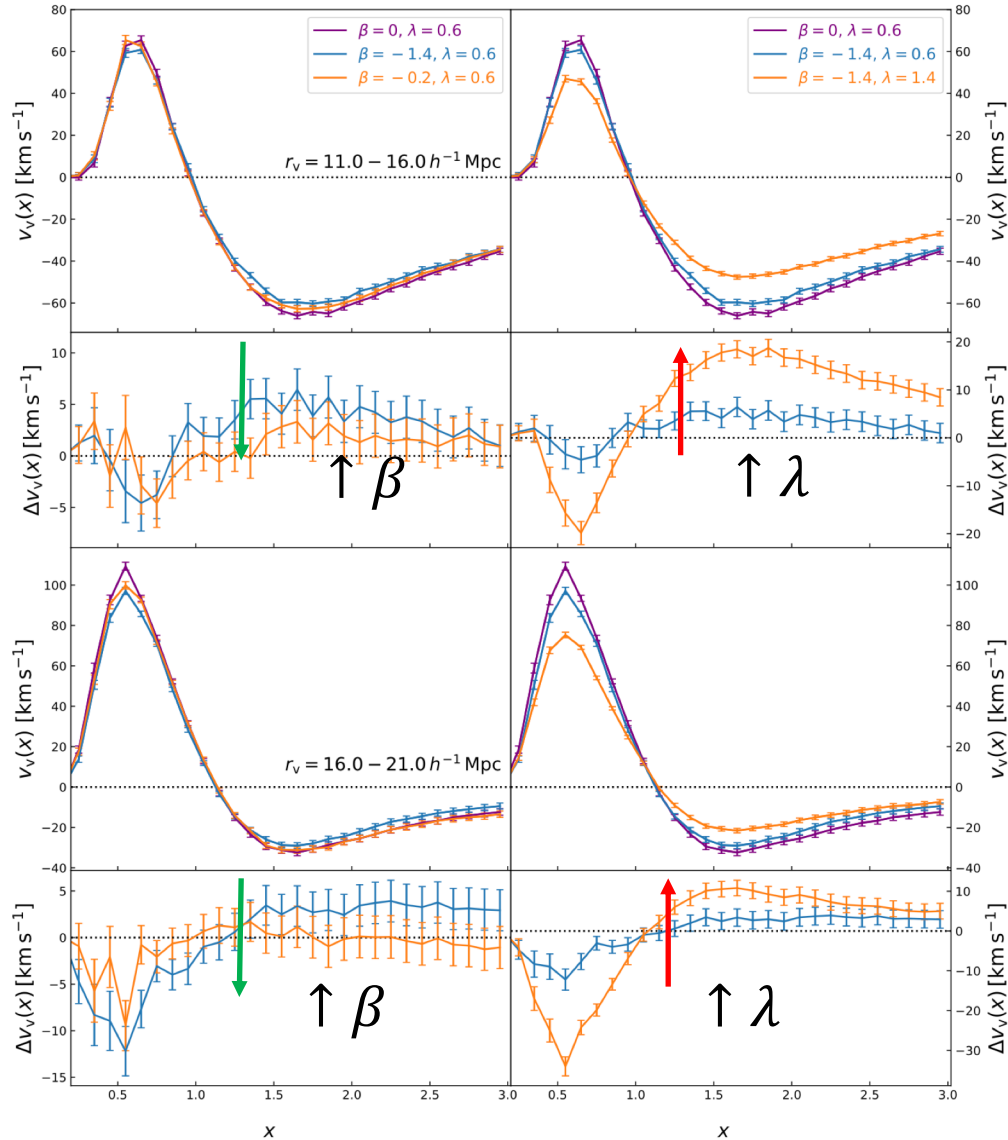
Void Radial Velocity Dispersion Profile σ_v



Void Density Profile δ_v

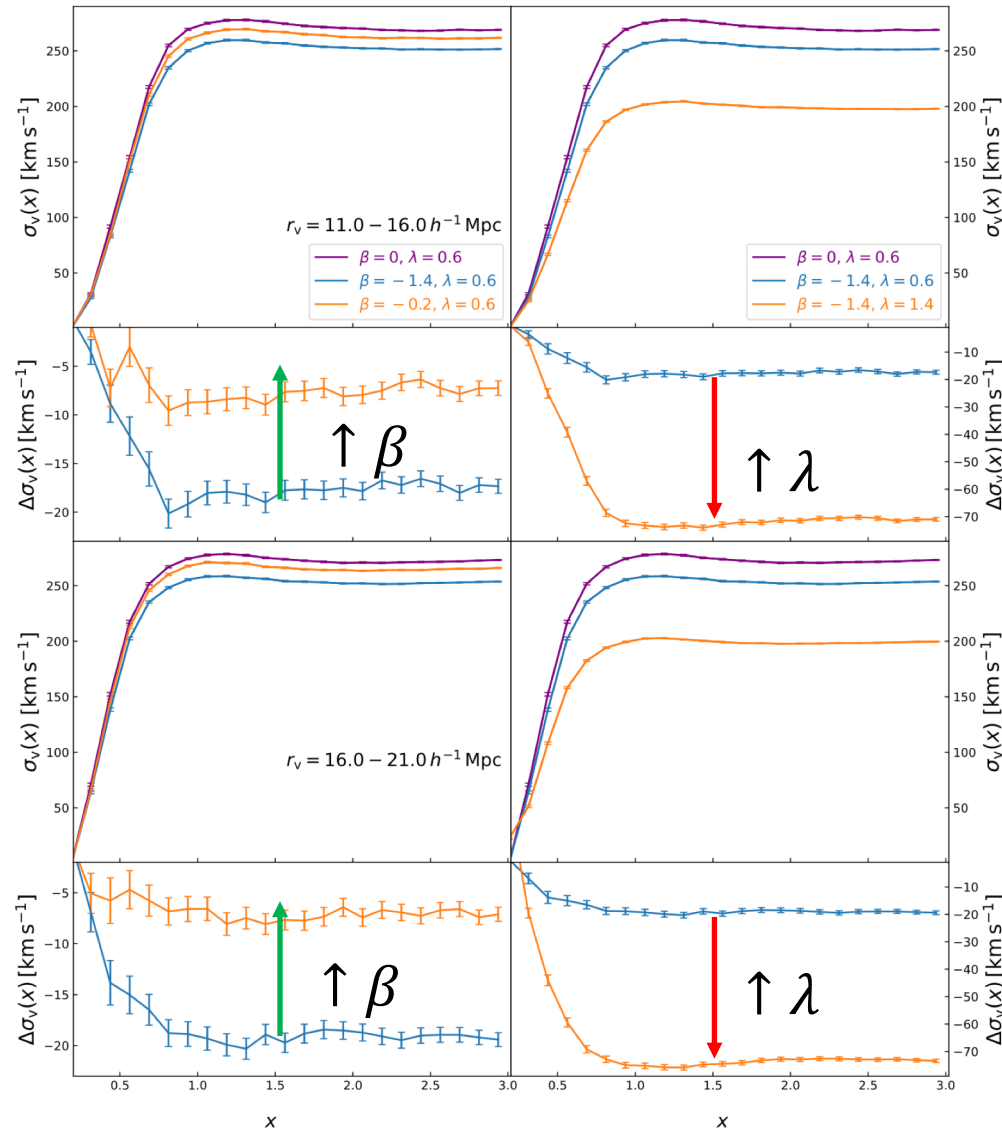


Appendix: Void radial velocity (CDM voids)



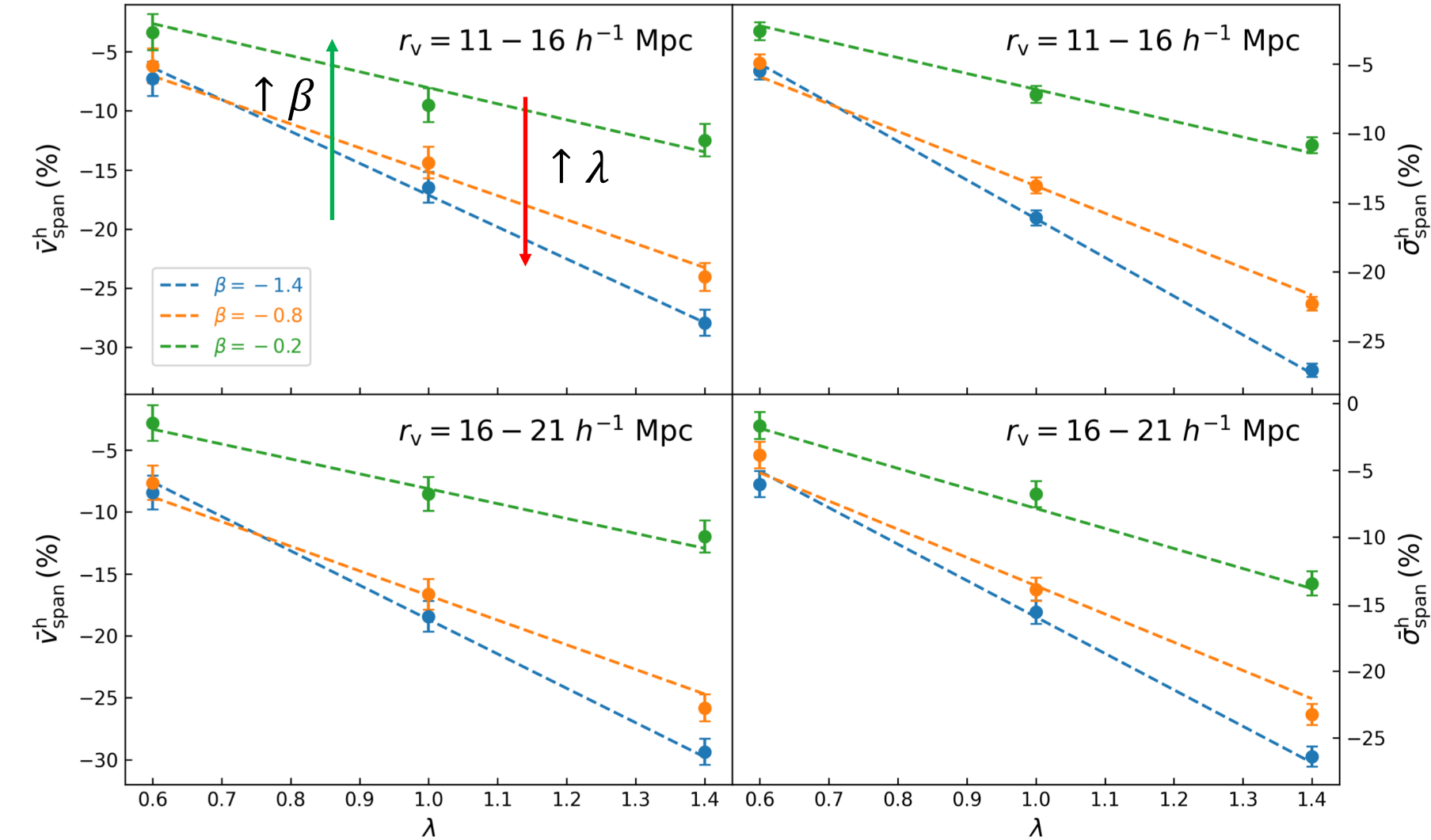
- Weaker coupling (increase in β) decreases the frictional damping on tracers $\rightarrow$ increases the outflow/inflow $|v_v|$
- Steeper potential's slope (increase in λ) increases the frictional damping on tracers $\rightarrow$ decreases $|v_v|$

Appendix: Void radial velocity dispersion (CDM voids)



- Weaker coupling (increase in β) decreases the frictional damping on tracers $\rightarrow$ increases the fluctuations σ_v
- Steeper potential's slope (increase in λ) increases the frictional damping on tracers $\rightarrow$ decreases the fluctuations σ_v

Appendix: 4-variable regression (Halo voids)



Up to $\sim 30\%$ deviation relative to the fiducial scenario

Appendix: 4-variable regression (CDM voids)

- Calculate the average velocity span (3 maximum and minimum) $\bar{v}_{\text{span}}$ and $\bar{\sigma}_{\text{span}}$ for all the cases
- Calculate the fractional deviation of $\bar{v}_{\text{span}}$ and $\bar{\sigma}_{\text{span}}$ relative to the uncoupled ($\beta = 0, \lambda = 0.6$) fiducial scenario and fit to a 4-variable regression

$$\Delta[\bar{v}_{\text{span}} | \bar{\sigma}_{\text{span}}] = c_{\beta} \Delta\beta + c_{\lambda} \Delta\lambda + c_{\beta\beta} \Delta\beta^2 + c_{\beta\lambda} \Delta\beta \Delta\lambda. \quad (6), \quad \text{with } \Delta\beta = \beta + 1.4, \Delta\lambda = \lambda - 0.6$$

Quantity	$r_v [h^{-1}\text{Mpc}]$	$c_{\beta} (\%)$	$c_{\lambda} (\%)$	$c_{\beta\beta} (\%)$	$c_{\beta\lambda} (\%)$	$R^2 (\bar{R}^2)$
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Appendix: Cosmological constant problem

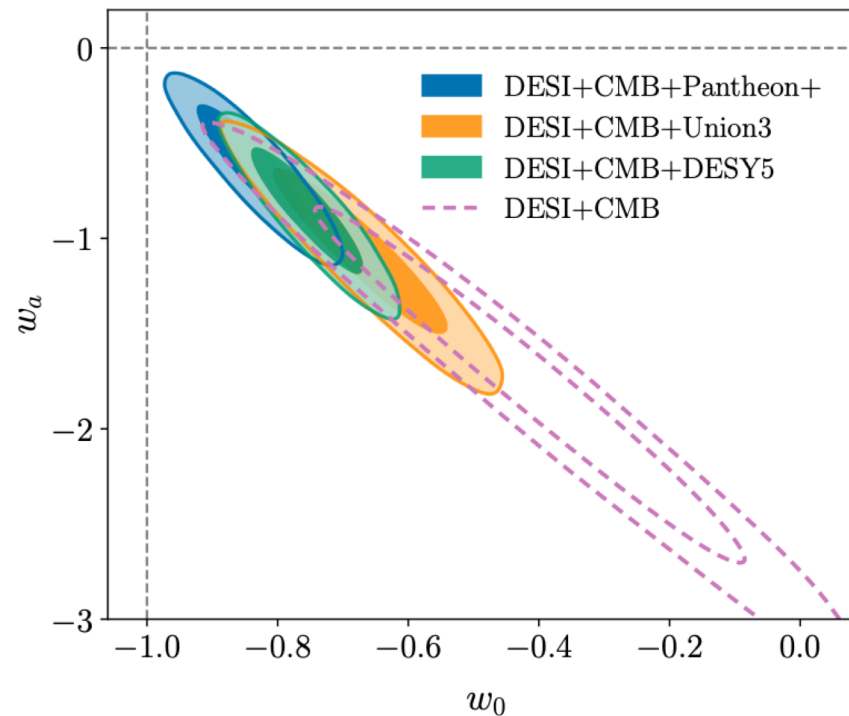
- Based on observations, the measurement of the dark energy (DE) density of Λ CDM is $\rho_{\text{eff}} = \frac{\Lambda_{\text{eff}}}{8\pi G} \sim 10^{-29} g\text{ cm}^{-3}$
- This differs from the vacuum energy density $\rho_{\text{vac}} \sim 10^{92} g\text{ cm}^{-3}$ predicted from QFT by a factor of 120

$$\Lambda_{\text{eff}} = \underbrace{\Lambda_0}_{\text{Bare Geometric constant}} + \underbrace{8\pi G \rho_{\text{vac}}}_{\approx 1.87 \times 10^{65} \text{ cm}^{-2}} \approx 1.1 \times 10^{-56} \text{ cm}^{-2}$$

- To recover the observed constants, Λ_0 should be negative and fine-tuned to cancel out ρ_{vac} to 120 decimal places, which lacks motivation

Appendix: DESI findings

- Recently, Dark Energy Spectroscopic Instrument (DESI) suggests a dynamical equation of state (EoS) $w_{DE} = w_0 + w_a(1 - a)$ for DE (for Λ CDM, $w_{DE} = -1$)
- In particular, it suggests that DE is weaker than that of the Λ CDM and weakens over time



Credit: DESI DR2 results