Gregory Horndeski, 'Horndeski Scalar Theory, Past, Present and Future'

# Towards Cosmology With Void-Lensing

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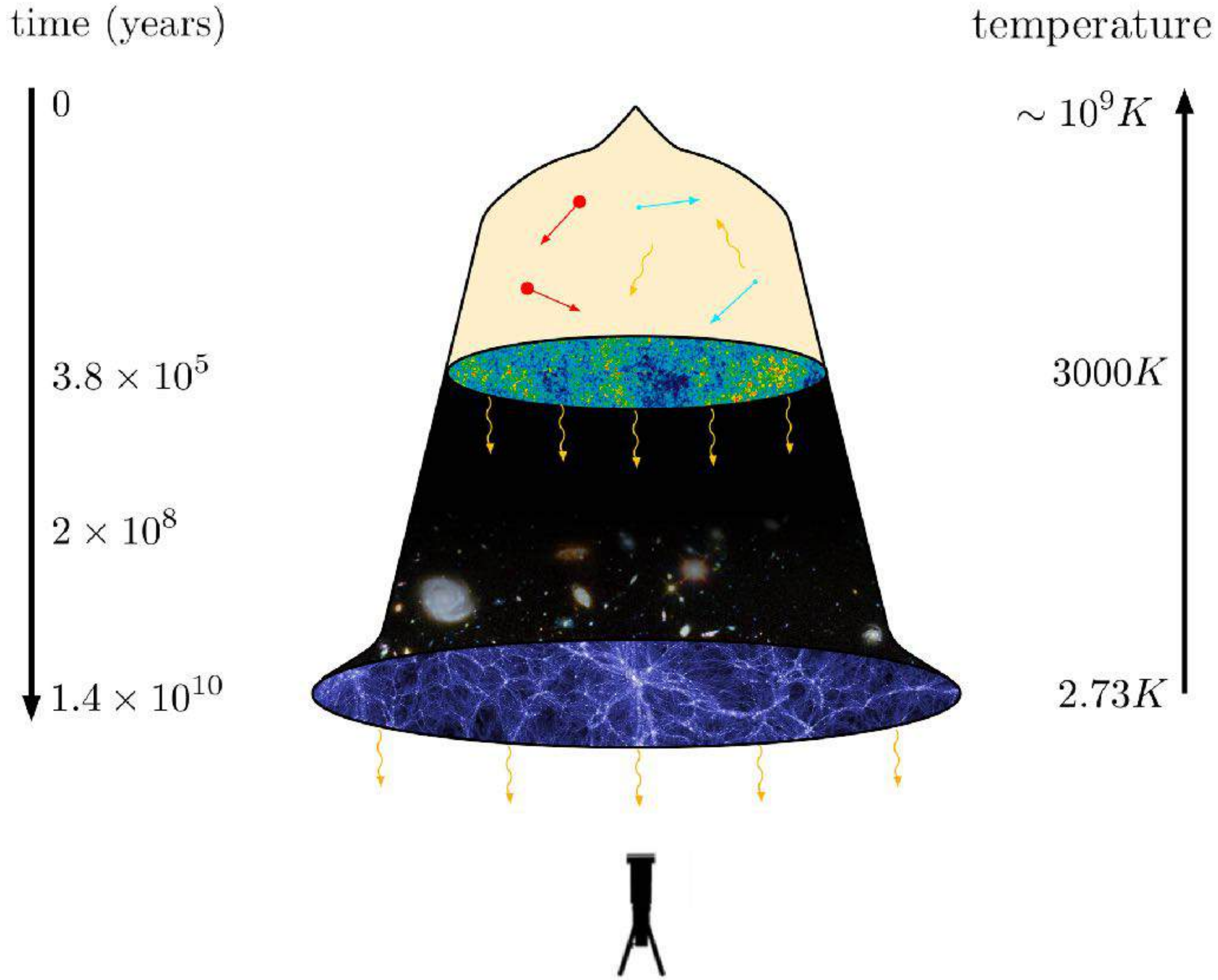
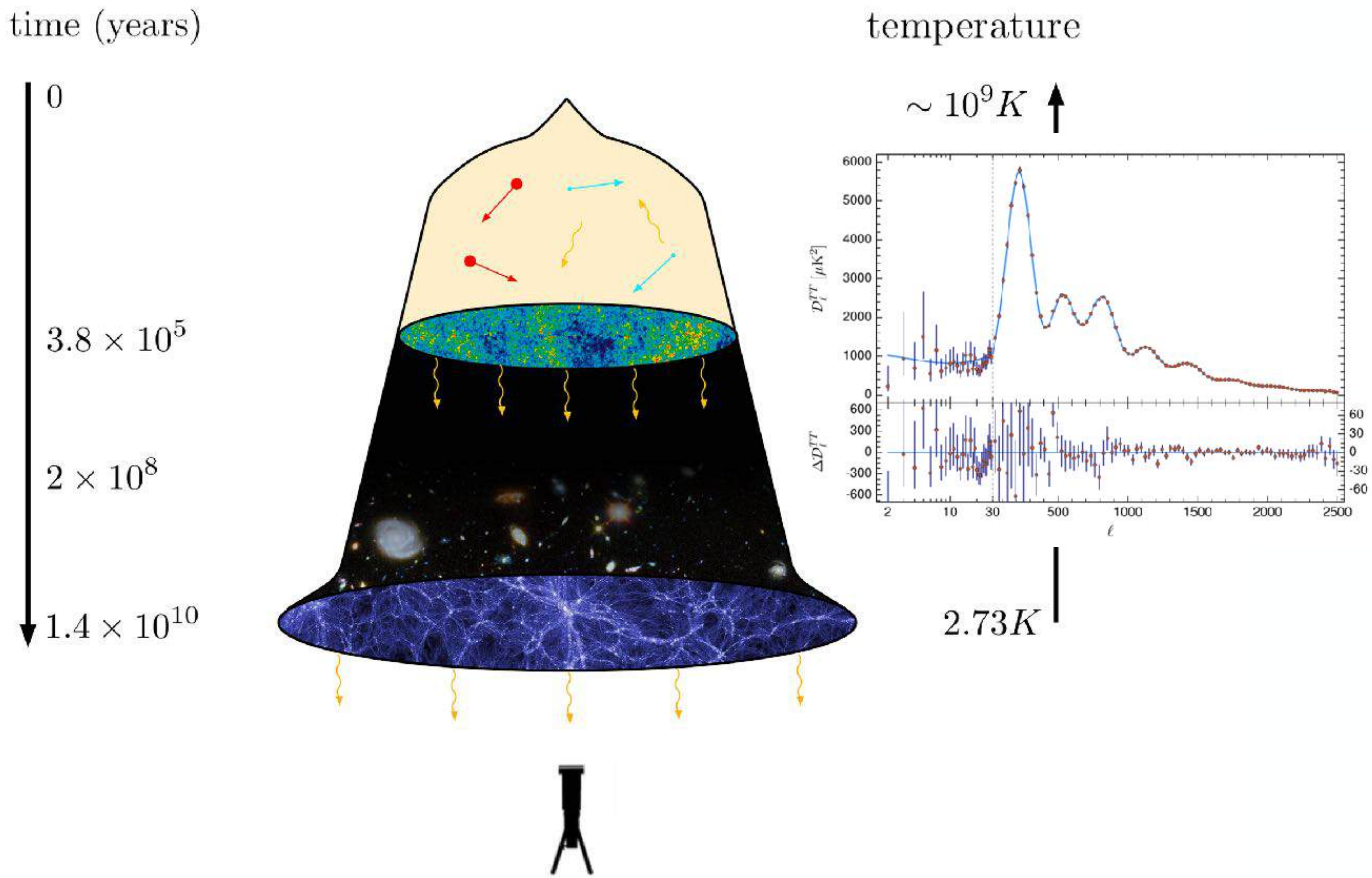
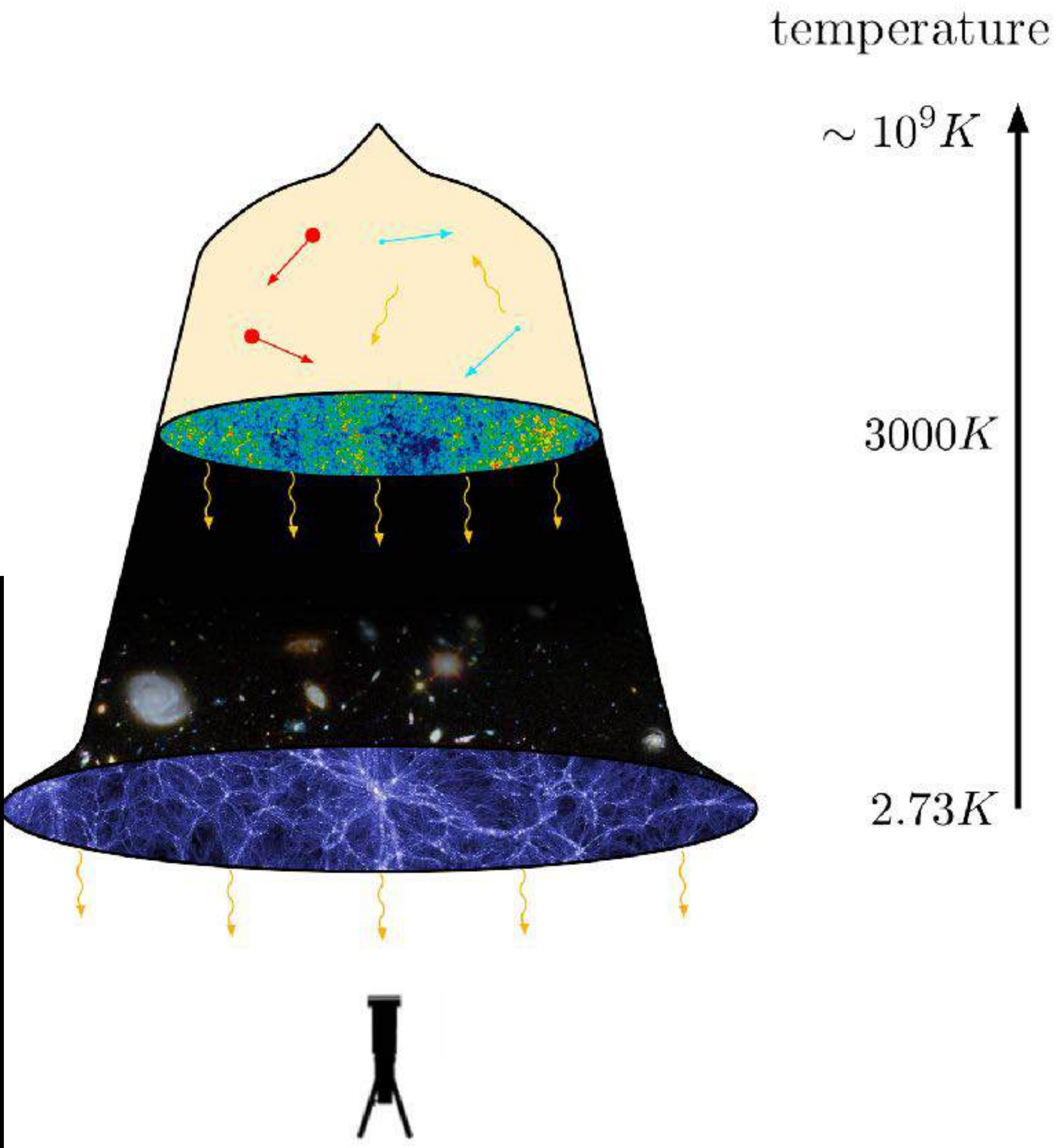
# What Is Observational Cosmology?

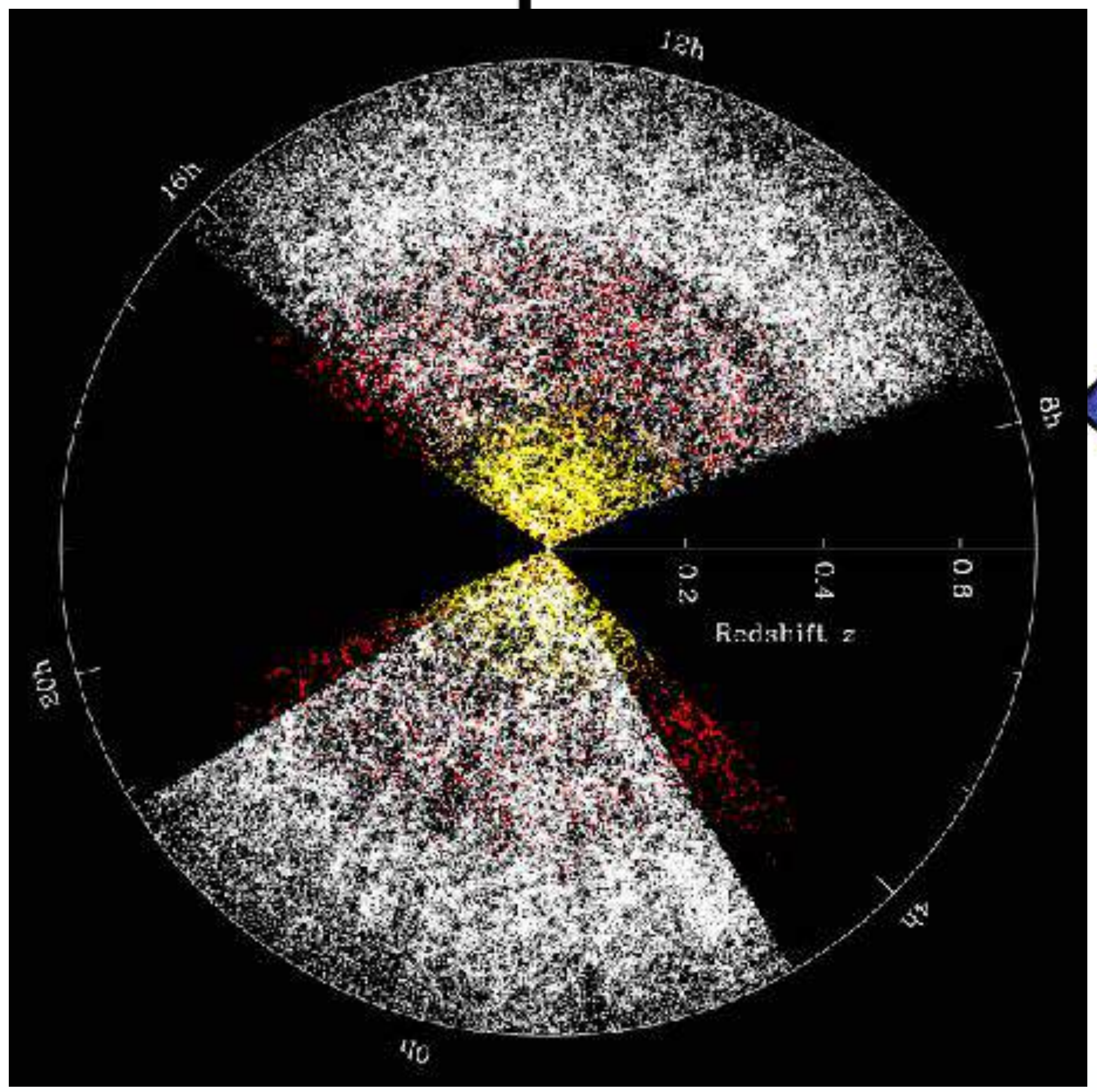


# What Is Observational Cosmology?



# What Is Observational Cosmology?




*Credit:Michael Blanton and SDSS collaboration*

# The Biggest Puzzle in Cosmology: the Cosmological Constant

The E-H action:

$$S = \frac{1}{2\kappa}\int \mathrm{d}^4x\sqrt{-g}\,\left(R - 2\Lambda_B\right) + S_{matter}\left[g_{\mu\nu}, \Psi\right]$$

$$\Rightarrow$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_{\mathrm{B}}g_{\mu\nu} = \kappa T_{\mu\nu}$$

The observed value for the cosmological constant should be

$$\Lambda_{eff} = \Lambda_B + \frac{\kappa}{(2\pi)^3}\int d\boldsymbol{k}\frac{1}{2}\omega^2(k) \qquad (\hbar = c = 1)$$

Cosmological observations suggest $\boxed{\Lambda_{eff} \simeq 10^{-3}eV}$

# The Biggest Puzzle in Cosmology: the Cosmological Constant

By using dimensional regularization:

$$\rho_{vac} = \sum_i n_i \frac{m_i^4}{64\pi} \ln\left(\frac{m_i^2}{\mu^2}\right)$$

Only the Higgs contribution gives $\sim 10^{44} eV$

$$\Lambda_{eff} = \Lambda_B + \rho_{vac} \simeq 10^{-3} eV!!$$

Fine tuning problems usually means we don't understand something!

# Modified Gravity

Gregory Horndeski, 'Horndeski Scalar Theory, Past, Present and Future'

# Lovelock's Theorem

"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."

$$S_{\text{grav}} = \frac{M_{Pl}^2}{2} \int \sqrt{-g}\, d^4x [R - 2\Lambda]$$

$$\delta S_{\text{grav}} = 0 \Leftrightarrow G_{\mu\nu} = 0$$

# Lovelock's Theorem

"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."

$$S_{\rm grav} = \frac{M_{Pl}^2}{2}\int\sqrt{-g}\,d^4x\left[\phi R - \frac{\omega(\phi)}{\phi}(\nabla\phi)^2 - 2V(\phi)\right]$$

$$S_{\rm grav} = \frac{M_{Pl}^2}{2}\int\sqrt{-g}\,d^4x\left[R+f(R)\right]$$

# Chameleon Gravity

$$S = \int \mathrm{d}x^4 \sqrt{-g}\left(\frac{M_{\mathrm{Pl}}^2}{2}R - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi)\right) - \int \mathrm{d}x^4 \mathscr{L}_m\left(\psi_m^{(i)}, g_{\mu\nu}^{(i)}\right)$$

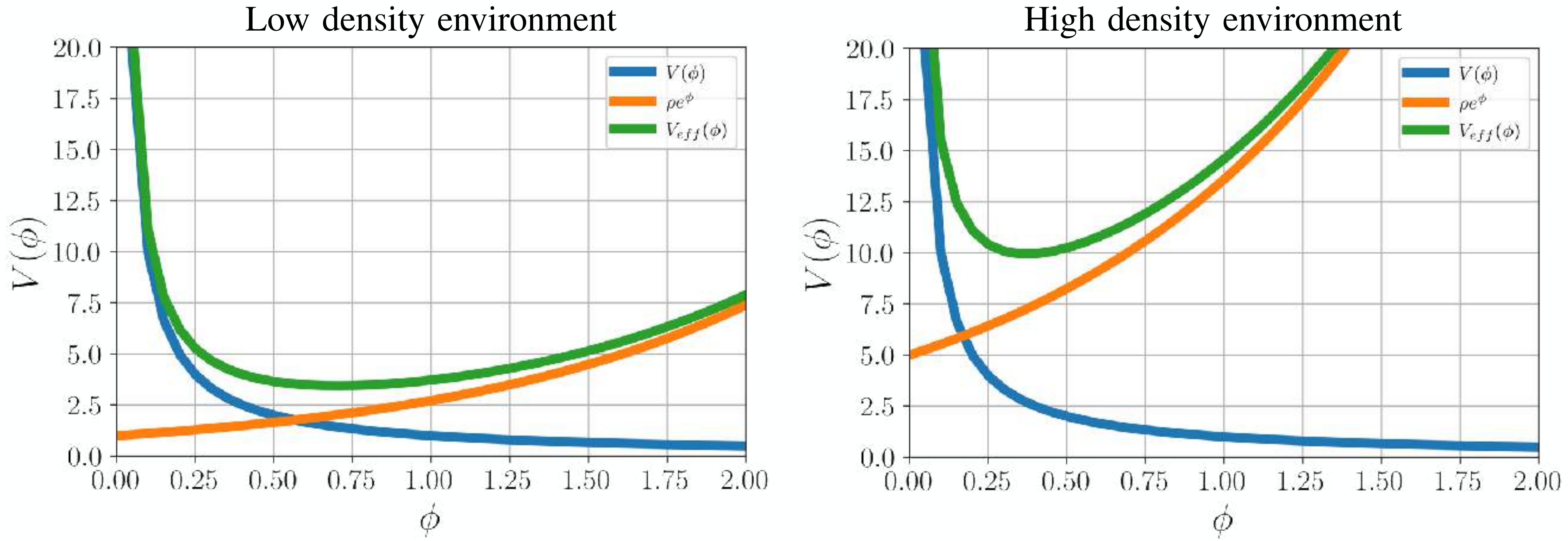
$$g_{\mu\nu}^{(i)} = A_i^2(\phi)g_{\mu\nu} \qquad A_i(\phi) = e^{\beta_i\phi/M_{Pl}}$$

$$\delta_\phi S = 0 \Leftrightarrow \Box\phi = V_{eff,\phi}(\phi)$$

$$V_{\mathrm{eff}}(\phi) = V(\phi) + \sum_i \rho_i e^{\beta_i\phi/M_{\mathrm{pl}}}$$

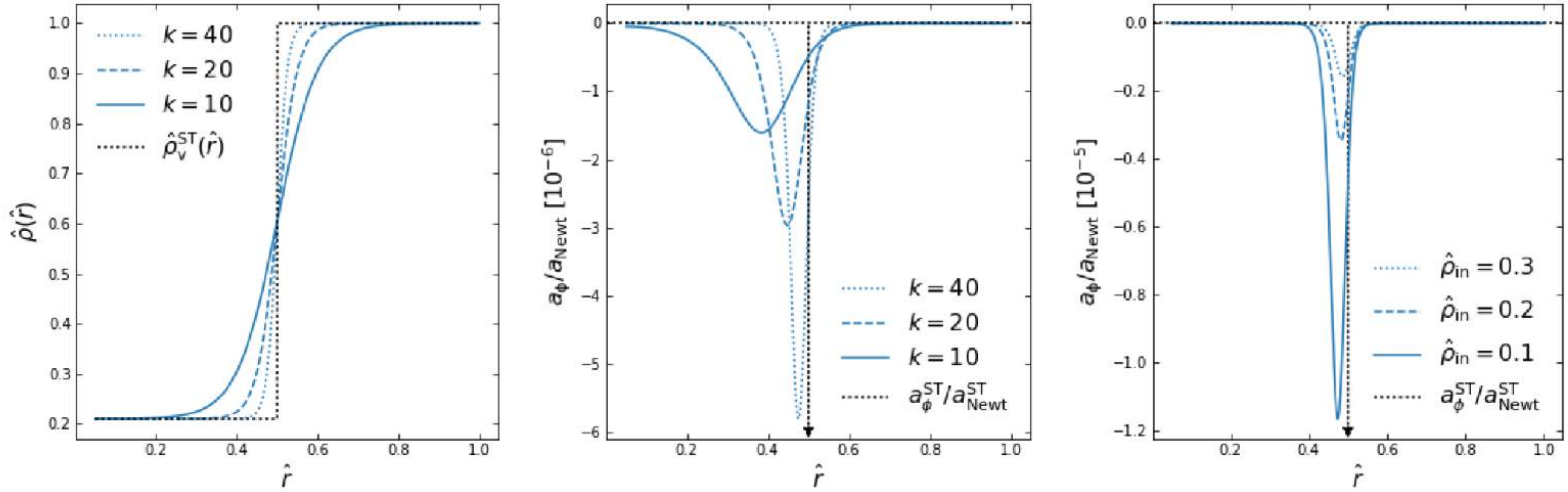
$$\boxed{\frac{\vec{F}_\phi}{m} = -\frac{\beta_i}{M_{Pl}}\vec{\nabla}\phi}$$

$$\phi(r) \sim A\frac{e^{-m_\phi r}}{r} + B \qquad m_\phi^2 \equiv V_{eff,\phi\phi}(\phi_{min})$$



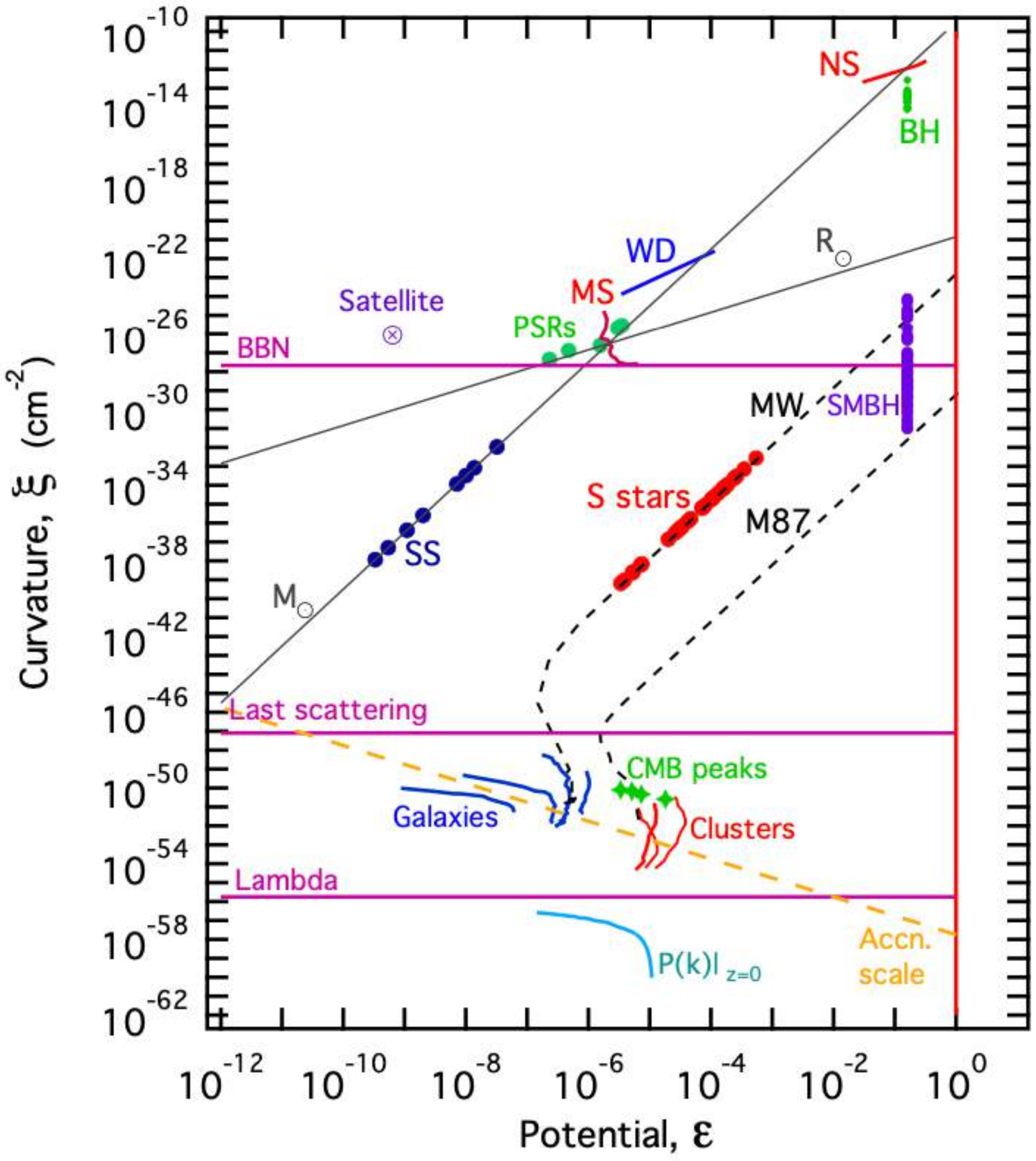
# The Chameleon Force on Voids

$$\ddot{x}^{\rho} + \Gamma^{(i)\rho}_{\mu\nu}\dot{x}^{\mu}\dot{x}^{\nu} \quad \Leftrightarrow \quad \boxed{\frac{\vec{F}_{\phi}}{m} = -\frac{\beta_i}{M_{Pl}}\vec{\nabla}\phi}$$




**Andrius Tamosiunas et al. (2022)**

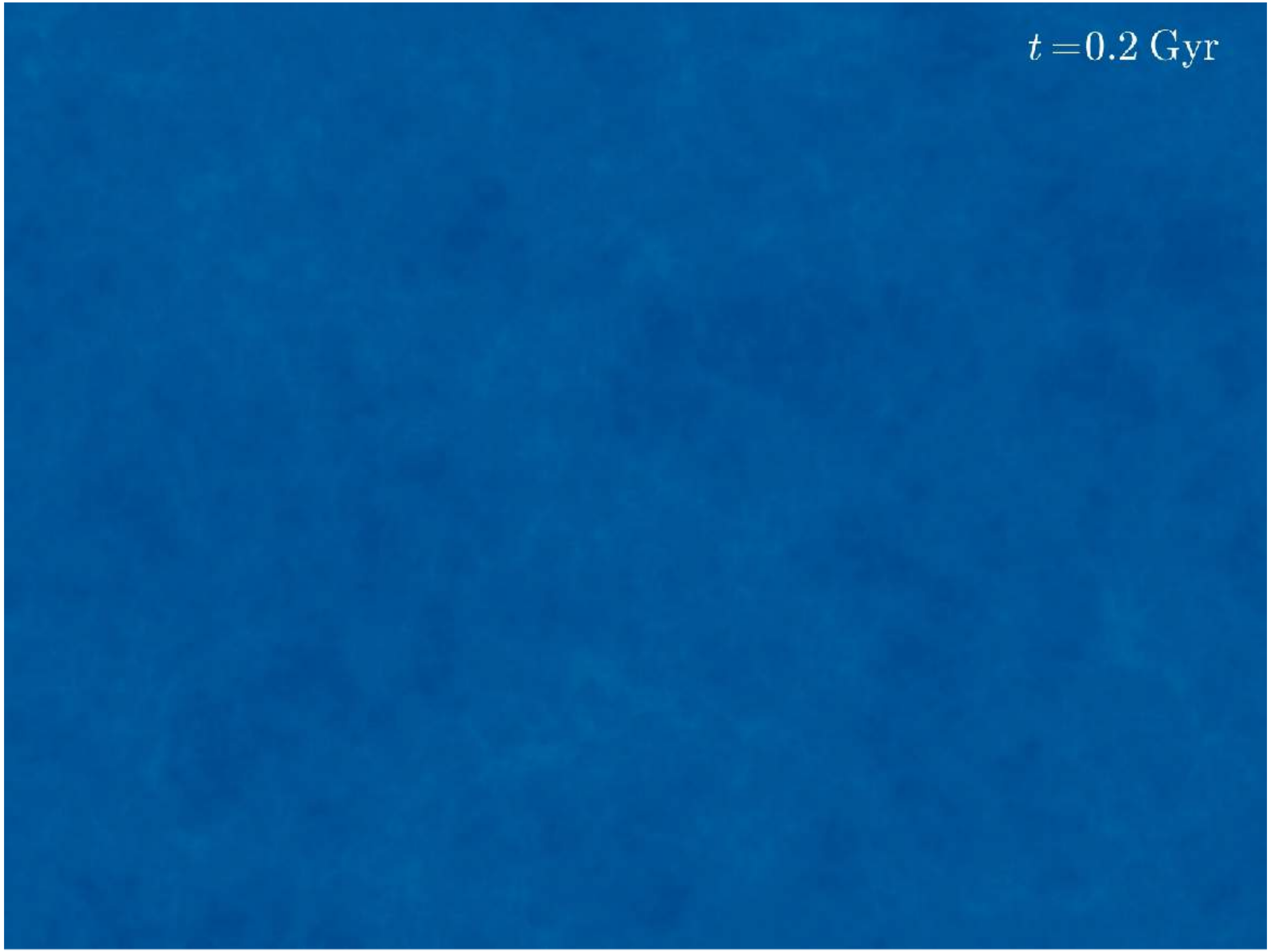
# Why To Test Gravity on Cosmological Scales? – Observational Reason




Credits: Psaltis, D. Testing general relativity with the Event Horizon Telescope

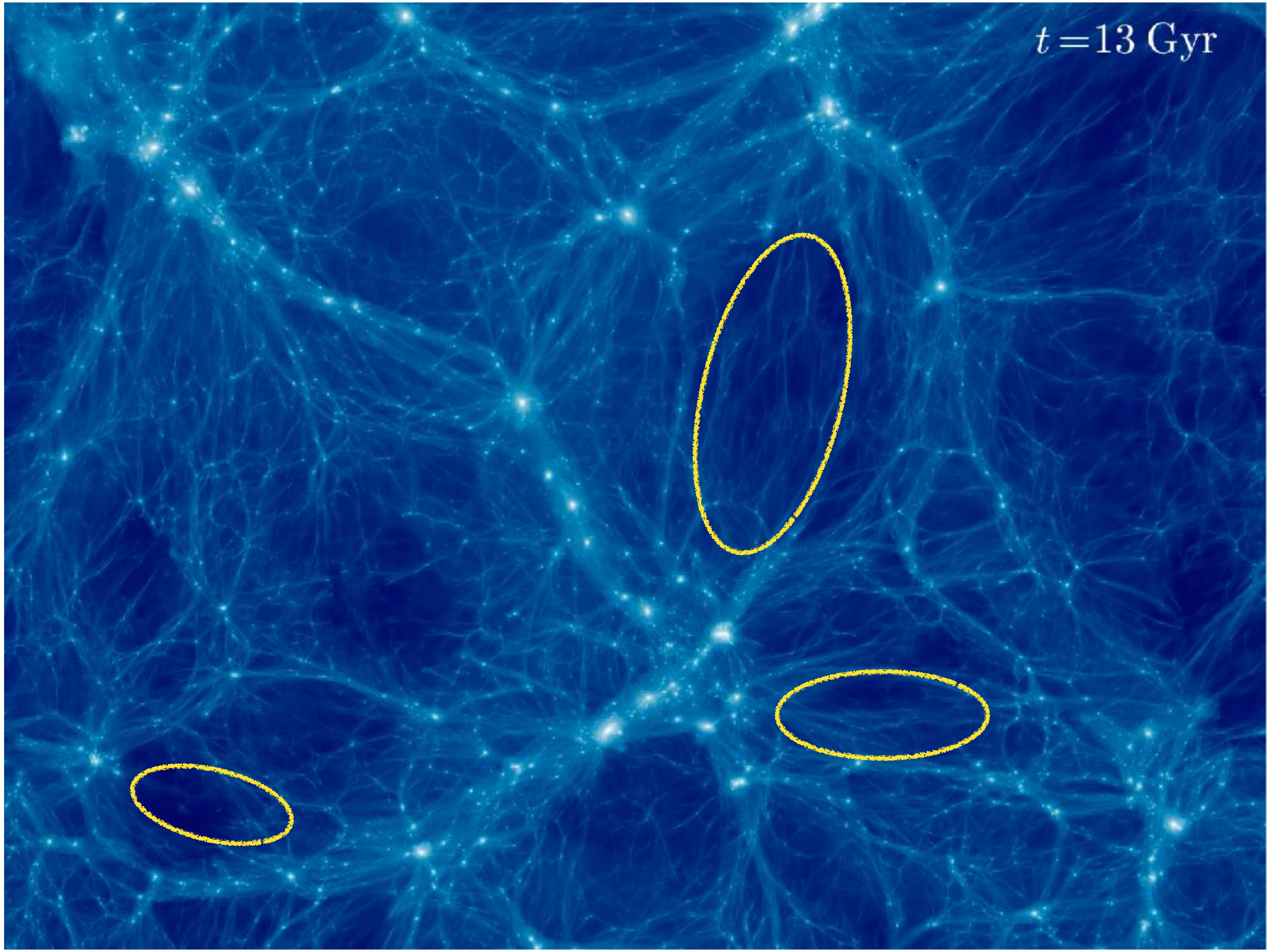

Cosmic Voids

# Why Voids?



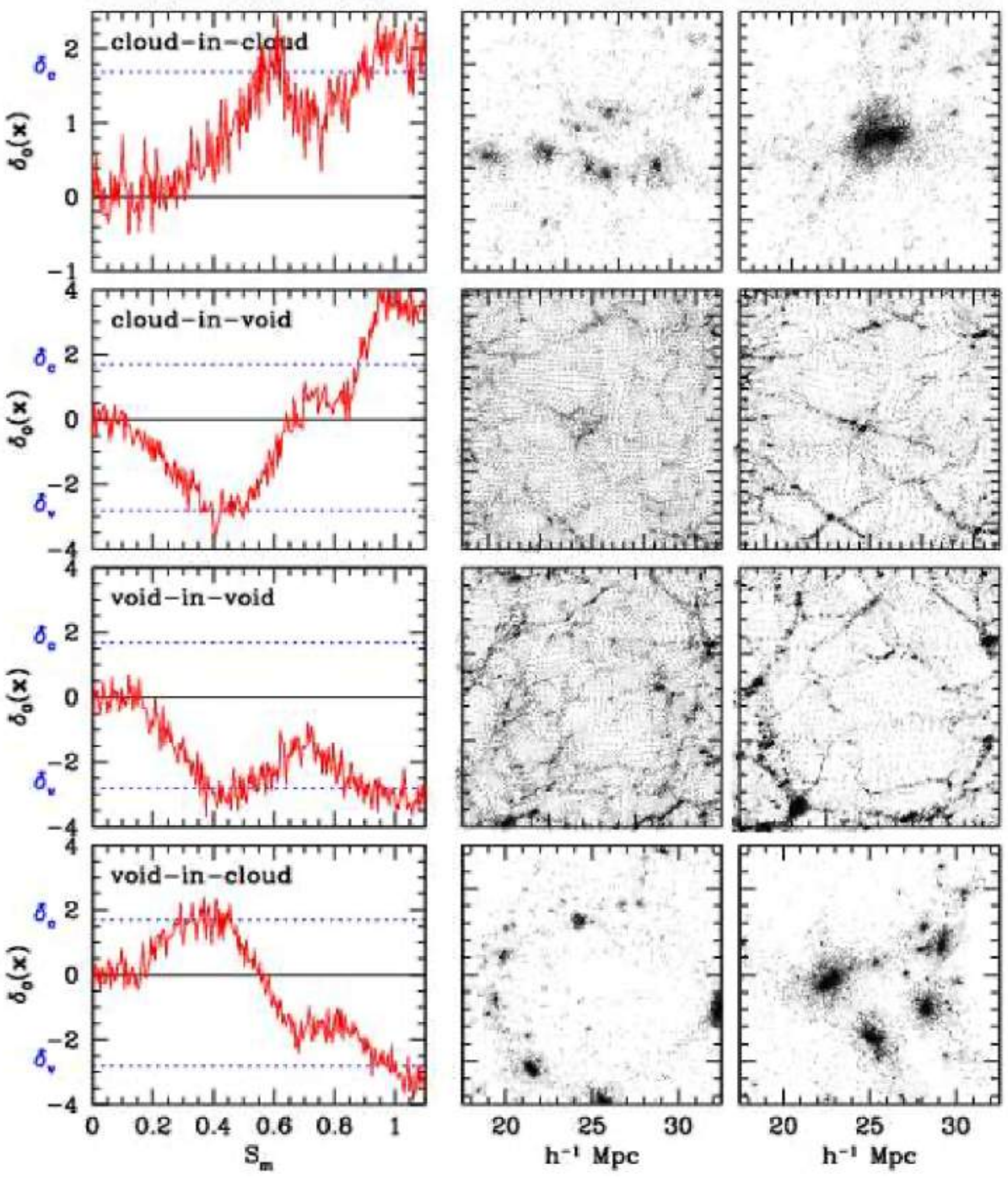

credits: Diemer & Mansfield

# Void Morphology




credits: Diemer & Mansfield

# How To Count Voids: Excursion Set Formalism in a Nutshell




**Sheth et al. (2004)**

$$\delta(R) \equiv \delta_R^{(1)}(\boldsymbol{q}) = \int d^3x W_R(x)\delta^{(1)}(\boldsymbol{q}+\boldsymbol{x})$$

$$S(R) \equiv \sigma^2(R) = \langle \delta^2(\boldsymbol{q}, R)\rangle$$

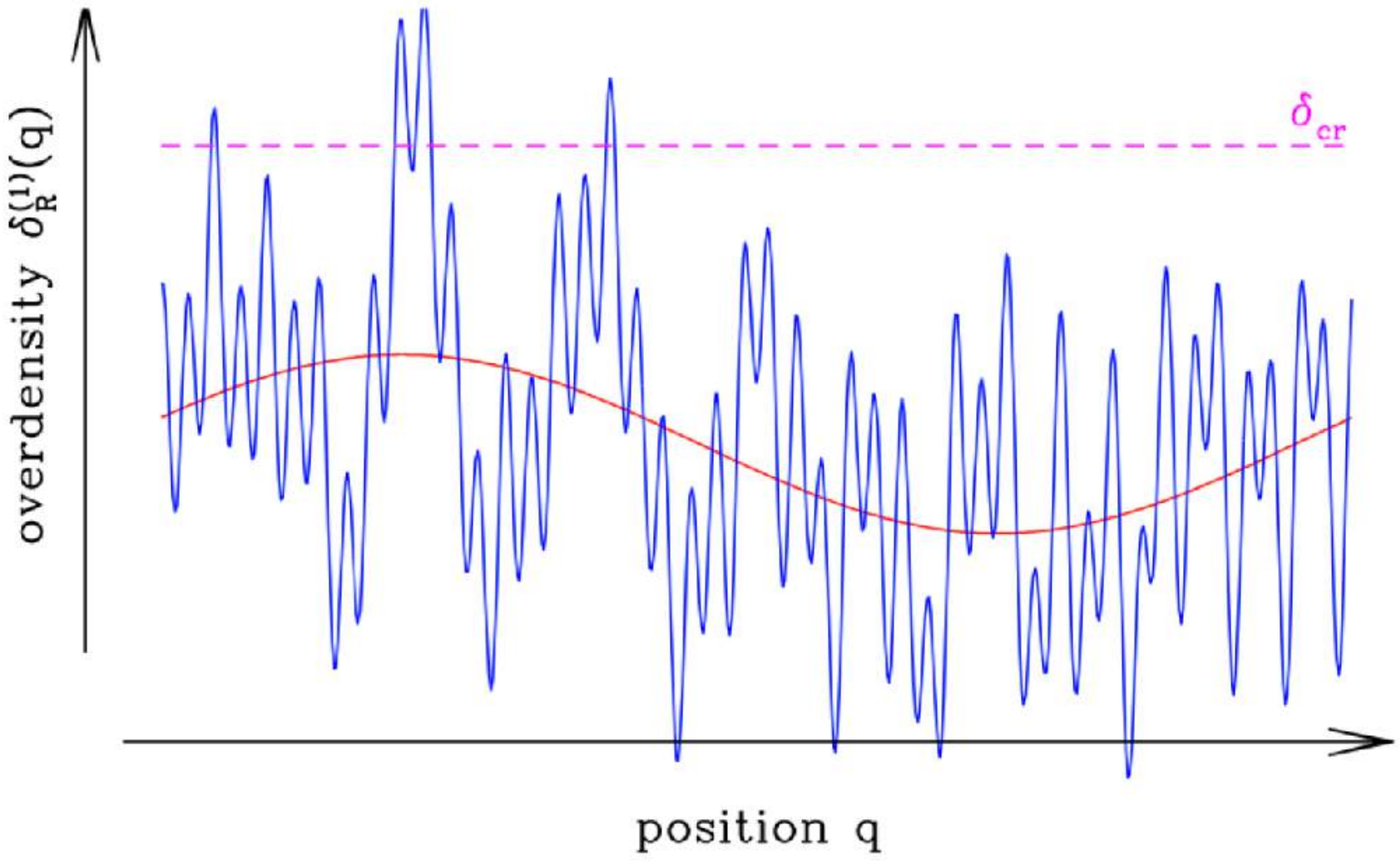
$$F(>M) = 1 - \int_{-\infty}^{\delta_v} d\delta \Pi(\delta; R_0)$$

$$\bar{n}_v(M) = -\bar{\rho}_m \frac{F(>M)}{dM}$$

$$\int_{-\infty}^{\delta_v} d\delta \Pi(\delta; S) = \int_{-\infty}^{\delta_v} d\delta \frac{1}{\sqrt{2\pi S}}\left[e^{-\delta^2/2S} - e^{-(2|\delta_v|-\delta)^2/2S}\right] = erf\left[\frac{\delta_v}{\sqrt{2S}}\right]$$


Weak Lensing
Credits: Jessie Muir

# Why Weak-Lensing?

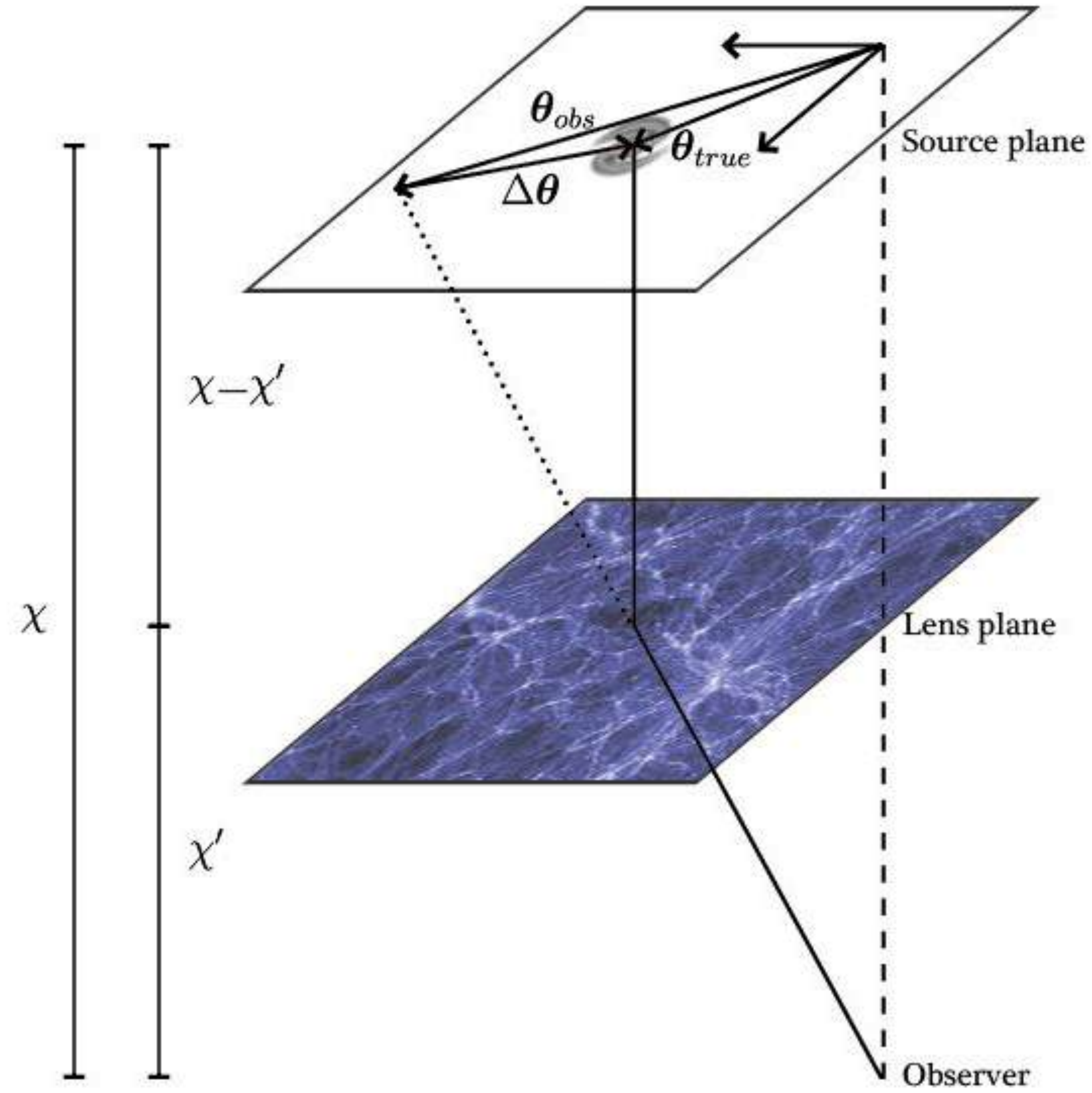



Desjacques et al. (2018)

$$\delta_g(\boldsymbol{x}, \tau) = \sum_{\mathcal{O}} b_{\mathcal{O}}(\tau)\mathcal{O}(\boldsymbol{x}, \tau)$$

$$\delta_g(\boldsymbol{x}, \boldsymbol{\tau}) \simeq b_g^{(1)}\delta_m(\boldsymbol{x}, \boldsymbol{\tau})$$

# Weak-Lensing Review




**Geodesic equation + scalar perturbations** $\Rightarrow$

$$\boxed{\begin{aligned}\theta^i &= \theta^i_s + \Delta\theta^i \\ \Delta\theta^i(\boldsymbol{\theta}) &= \frac{2}{c^2}\int_0^{\chi} d\chi' \Phi_{,i}\left(\boldsymbol{x}\left(\boldsymbol{\theta},\chi'\right)\right)\chi'\left(1-\frac{\chi'}{\chi}\right)\end{aligned}}$$

$$\psi_{ij} \equiv \frac{\partial \Delta\theta^i}{\partial\theta^j} = \frac{\partial^2}{\partial\theta^i\partial\theta^j}\phi_{\mathrm{L}}(\boldsymbol{\theta}) = \frac{2}{c^2}\int_0^{\chi} d\chi' \Phi_{,ij}\left(\boldsymbol{x}\left(\boldsymbol{\theta},\chi'\right)\right)\chi'\left(1-\frac{\chi'}{\chi}\right)$$

$$A_{ij} \equiv \frac{\partial\theta^i_S}{\partial\theta^j} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

$$A_{ij} = \delta_{ij} + \psi_{ij}$$

$$\boxed{\begin{aligned}&\kappa = \frac{\psi_{11}+\psi_{22}}{2} = \frac{2}{c^2}\int_0^{\chi} d\chi' \nabla^2\Phi\left(\boldsymbol{x}\left(\boldsymbol{\theta},\chi'\right)\right)\chi'\left(1-\frac{\chi'}{\chi}\right) \\ &\gamma_1 = -\frac{\psi_{11}-\psi_{22}}{2} \qquad \gamma_2 = -\psi_{12}\end{aligned}}$$

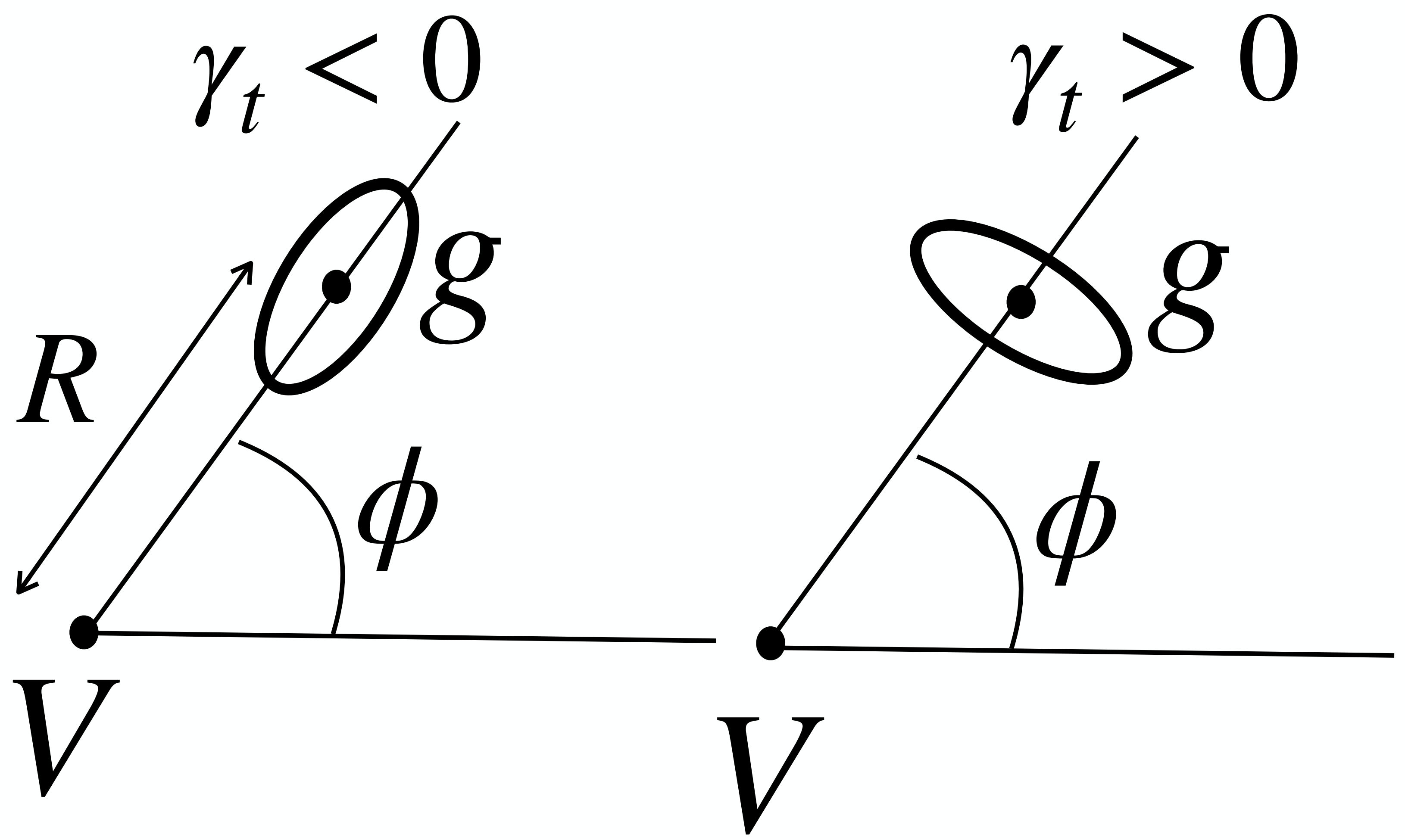
# Weak-Lensing Review

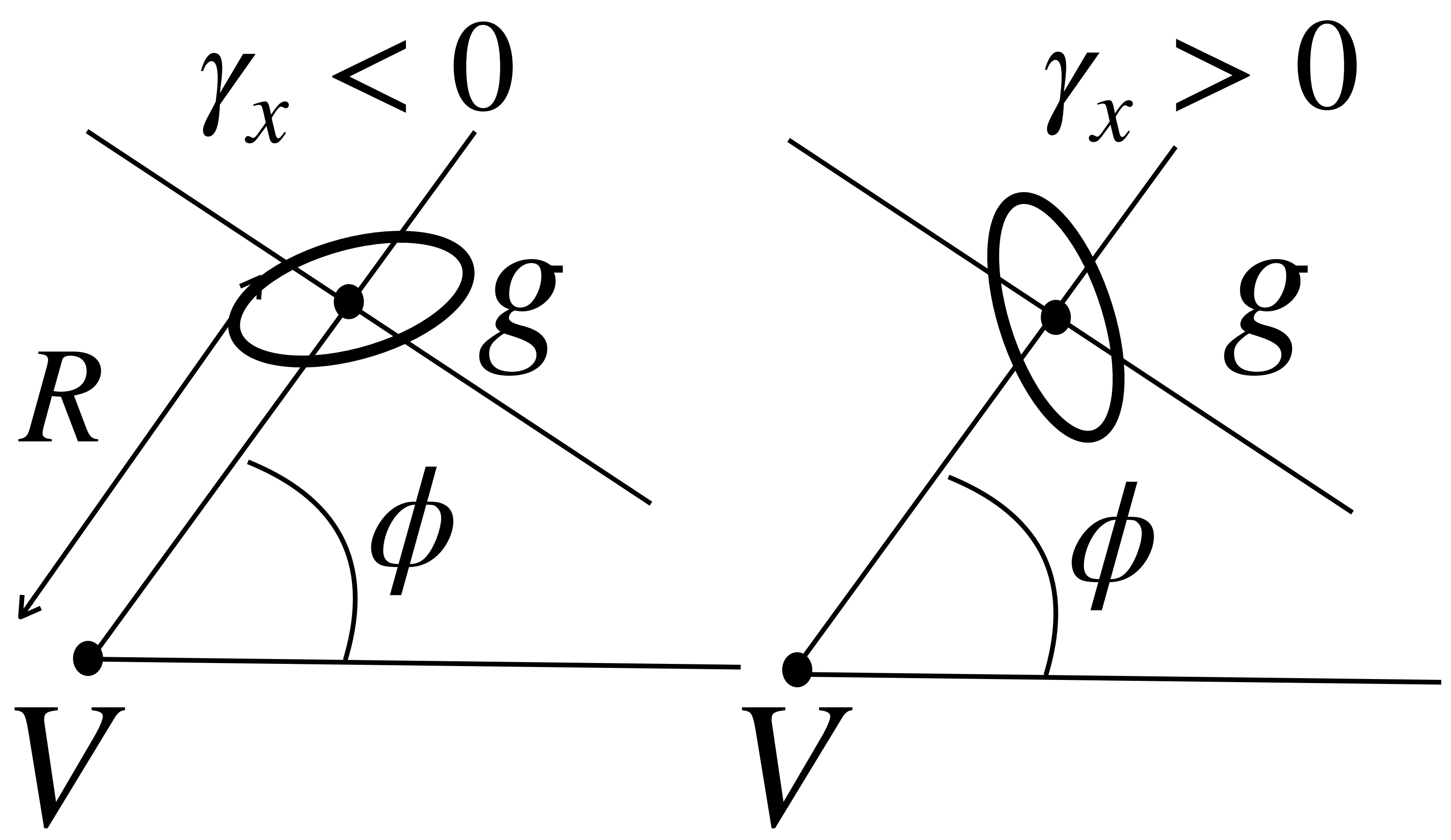
**Mean convergence within $\theta$:**

$$\bar{\kappa}(\leq\theta) = \frac{1}{c^2\pi\theta^2}\int_{|\boldsymbol{\theta}'|<\theta} \mathrm{d}^2\theta'\kappa\left(\boldsymbol{\theta}'\right) = \frac{2}{c^2\theta^2}\int_0^\theta \mathrm{d}\theta'\theta'\langle\kappa\rangle(\theta') \quad \langle\kappa\rangle(\theta') = (2\pi)^{-1}\int_0^{2\pi}\mathrm{d}\varphi\kappa\left(\theta',\varphi\right)$$

$$\boxed{\left\langle\gamma_{\mathrm{t}}\right\rangle(\theta) = \bar{\kappa}(\leq\theta) - \langle\kappa\rangle(\theta)}$$

$$\gamma_t = -\Re\{(\gamma_1 + i\gamma_2)e^{-2i\phi}\} \quad (\gamma_x = -\Im\{(\gamma_1 + i\gamma_2)e^{-2i\phi}\})$$



# Weak-Lensing Review

**Under the thin lens approximation:**

$$\kappa(\boldsymbol{\theta}) = \frac{4\pi G}{c^2}\frac{\chi_1\chi_{1s}}{\chi_s}\int_{\chi_1-\Delta\chi/2}^{\chi_1+\Delta\chi/2} \mathrm{d}\chi\bar{\rho}\delta(\chi\boldsymbol{\theta},\chi) = \frac{\Sigma(\boldsymbol{\theta})}{\Sigma_{cr}}$$

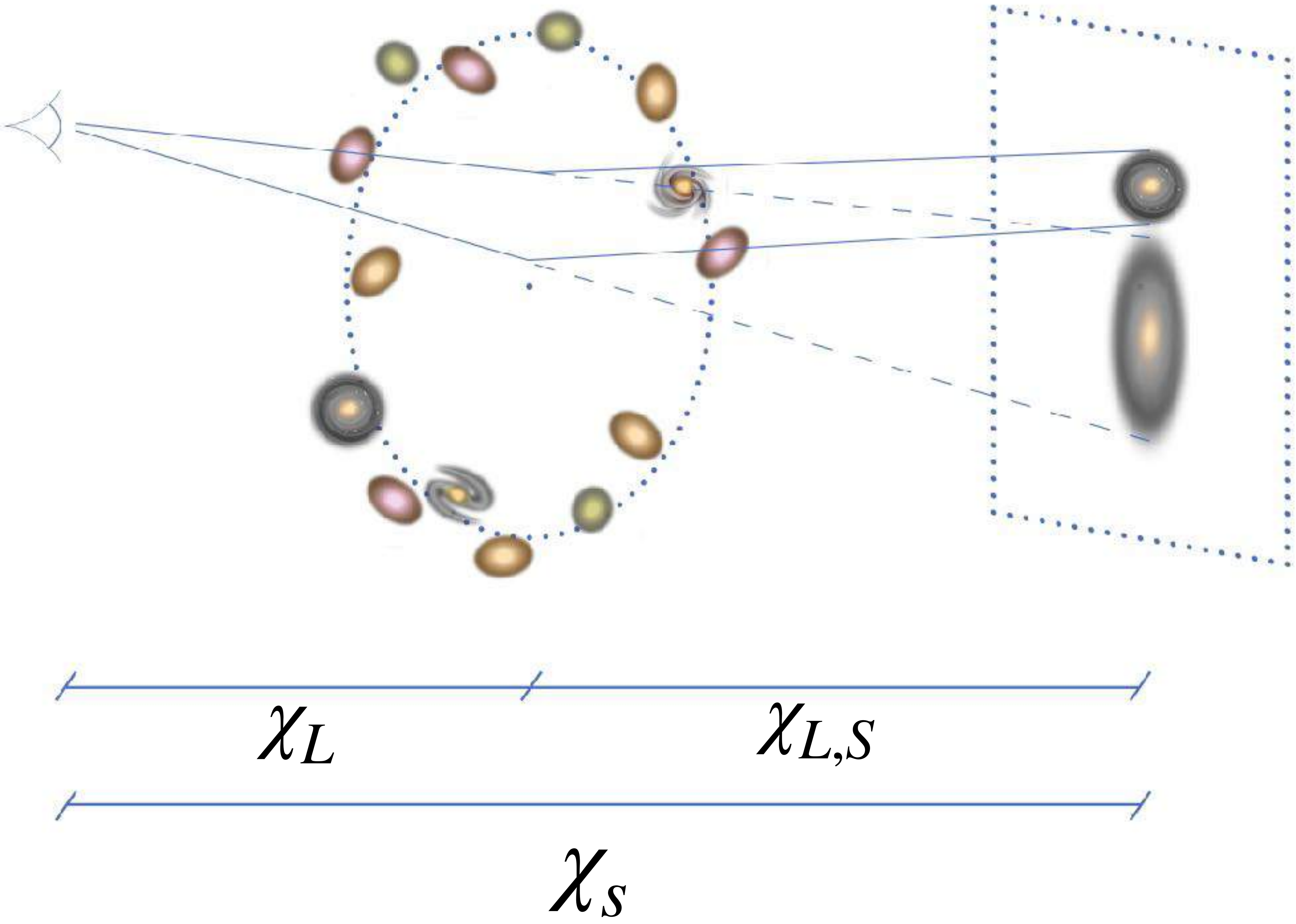
**By defining**

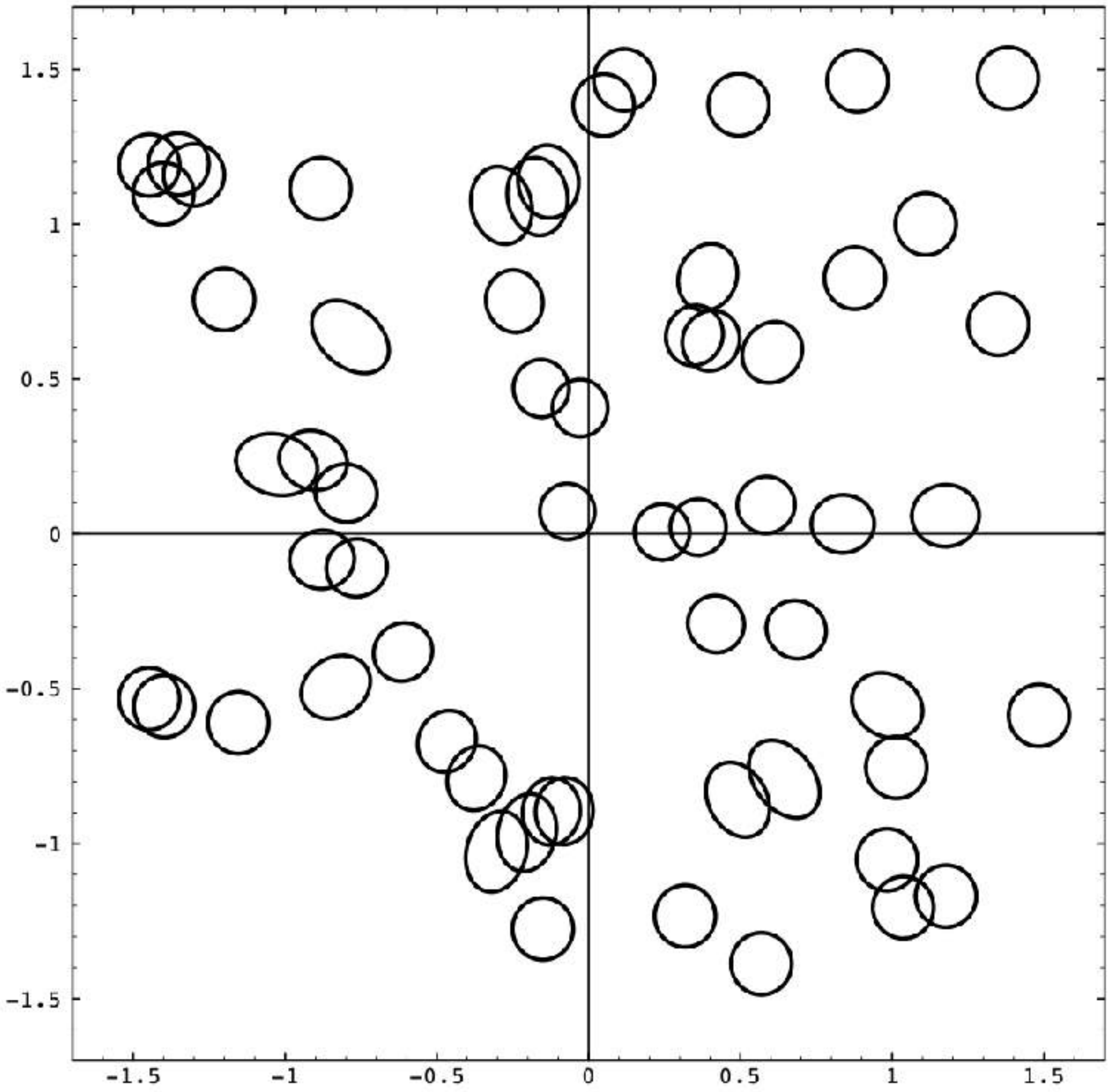
$$\Delta\Sigma(\theta) = \bar{\Sigma}(\leq \theta) - \langle\Sigma\rangle(\theta)$$

$$\boxed{\Delta\Sigma_{t,x}(\theta) = \Sigma_{\mathrm{cr}}\left\langle\gamma_{t,x}\right\rangle(\theta)}$$


Void – Lensing

# WL Voids




**Amendola et al. (1998)**

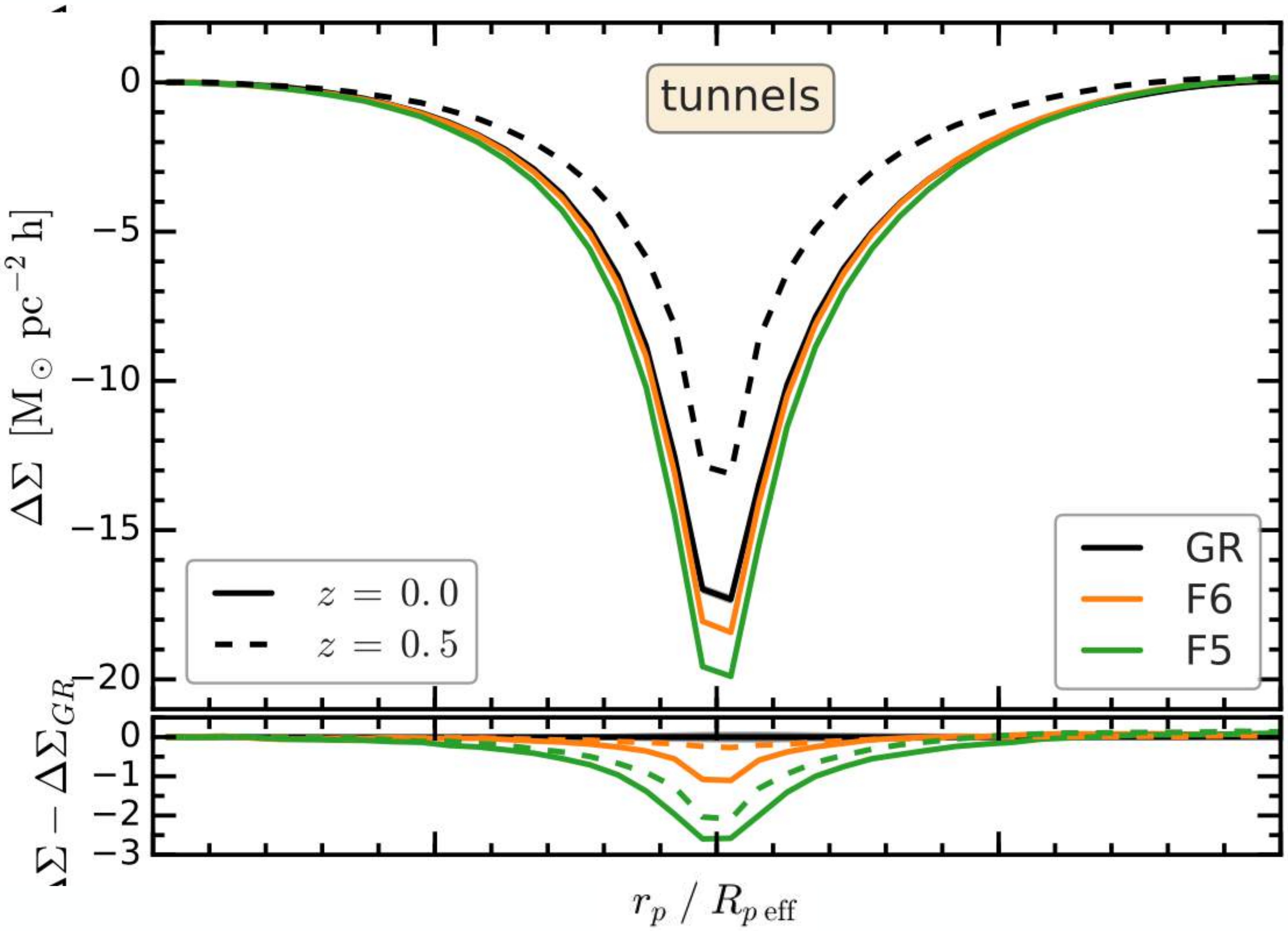
# Void-Lensing and MG

$$S_{\mathrm{grav}} = \frac{M_{Pl}^2}{2}\int \sqrt{-g}\,d^4x\,\left[R + f(R)\right]$$

$$\nabla^2\Phi = \frac{16\pi G}{3}a^2\delta\bar{\rho}_m + \frac{a^2}{6}\delta R(f_R)$$

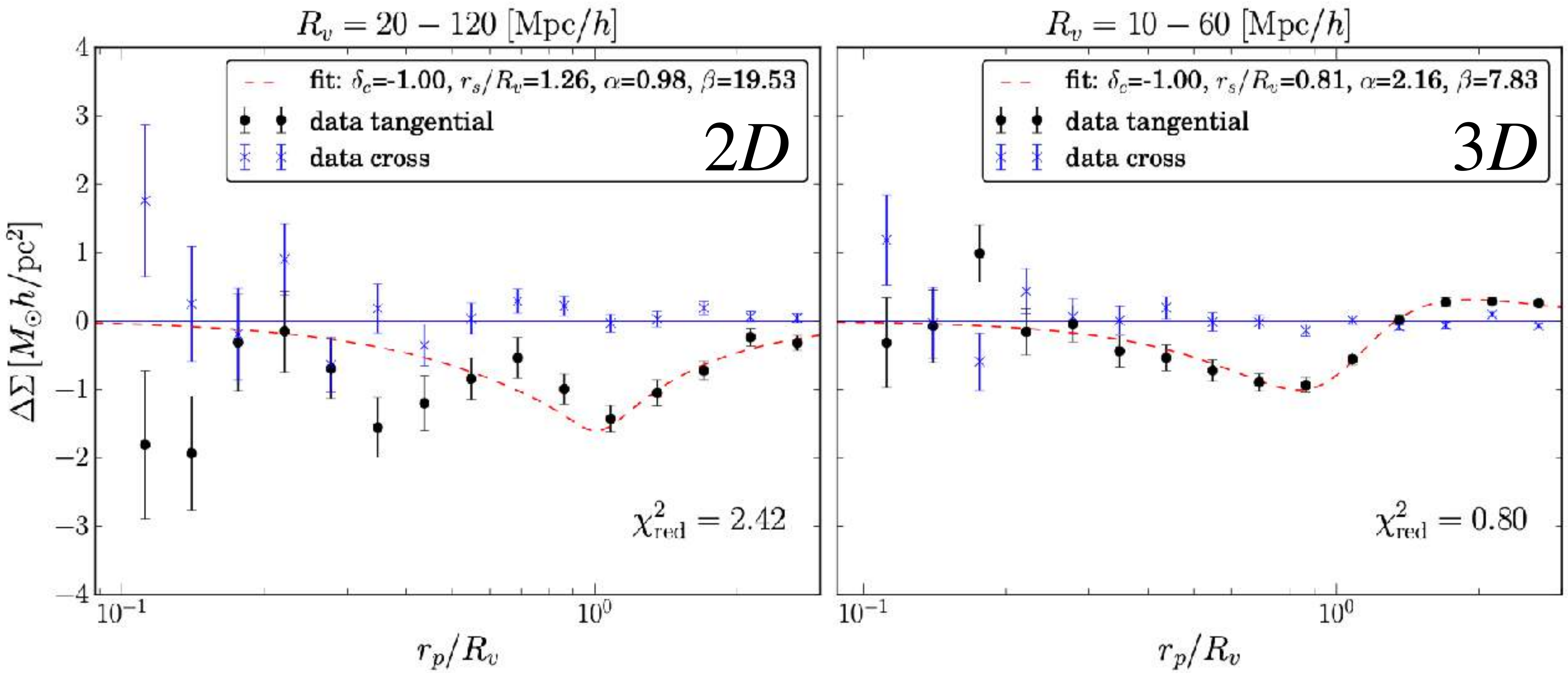
$$\nabla^2(\Psi - \Phi) = \nabla^2\delta f_R$$

$$\nabla^2(\Psi + \Phi) = 8\pi G a^2\delta\bar{\rho}_m$$

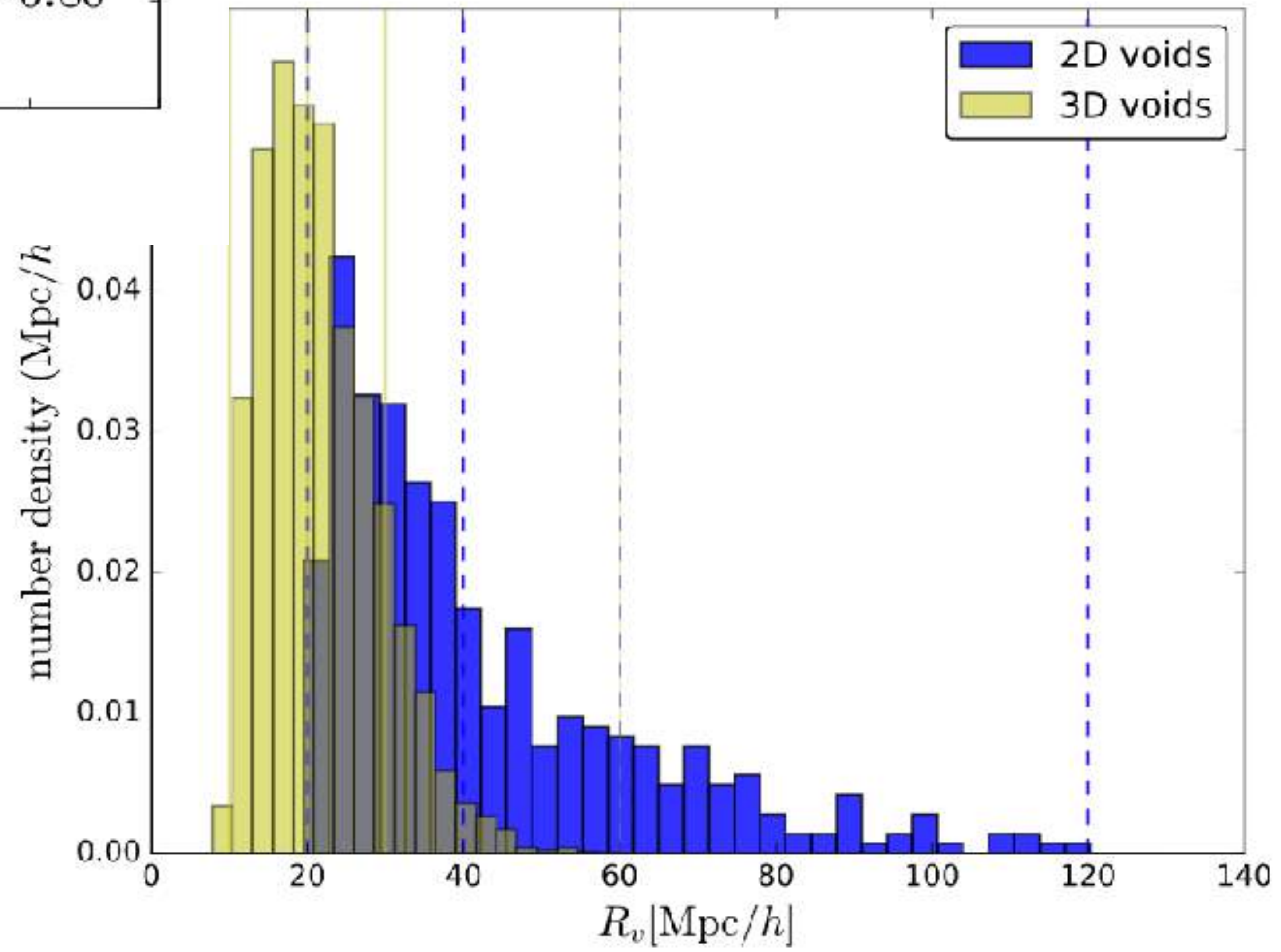



**Marius Cautun et al. (2018)**

# Void Lensing (DES)

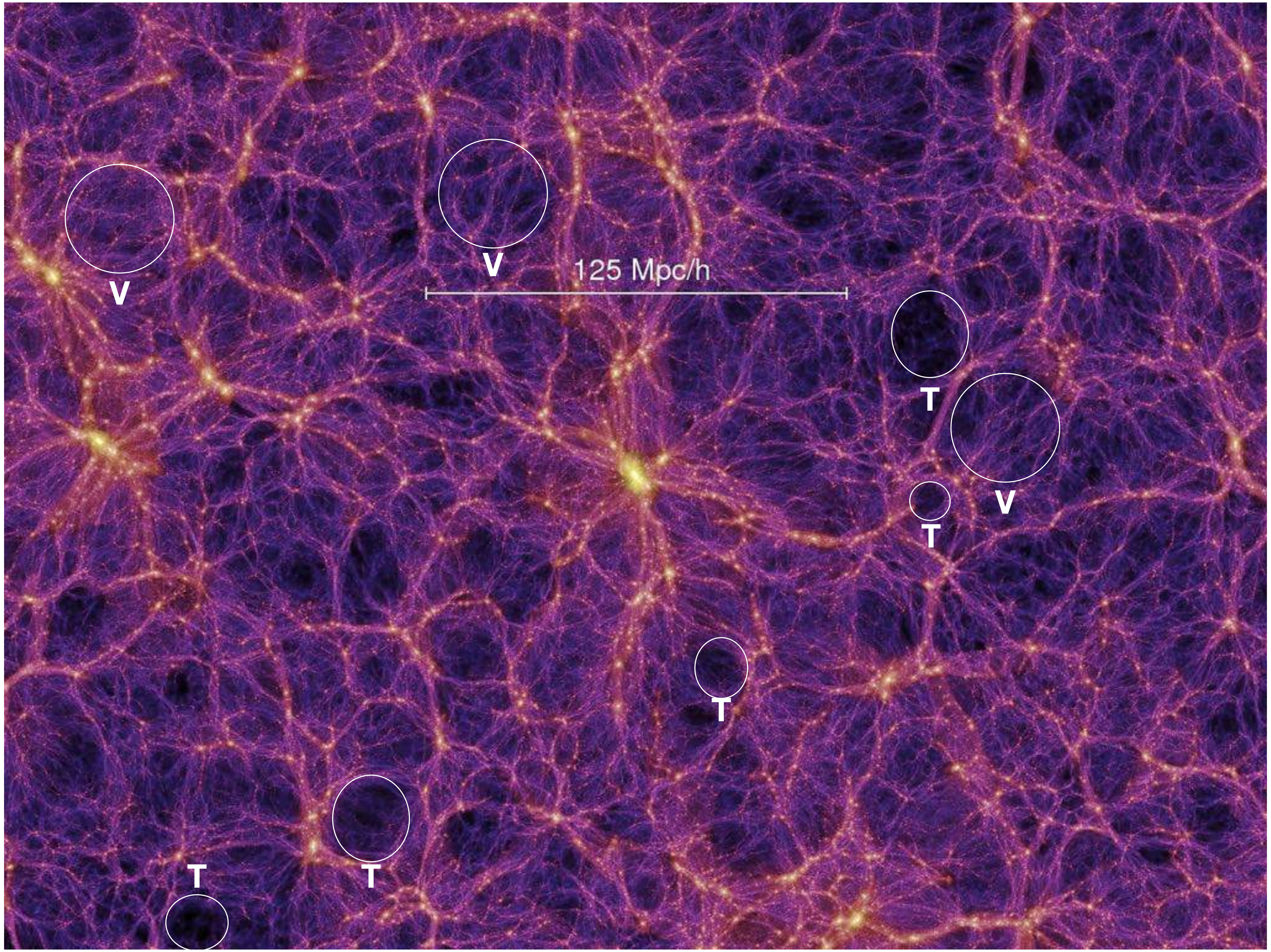



$$S/N_{2D} = 10 \quad S/N_{3D} = 14$$




**Y. Fang et al. (2019)**

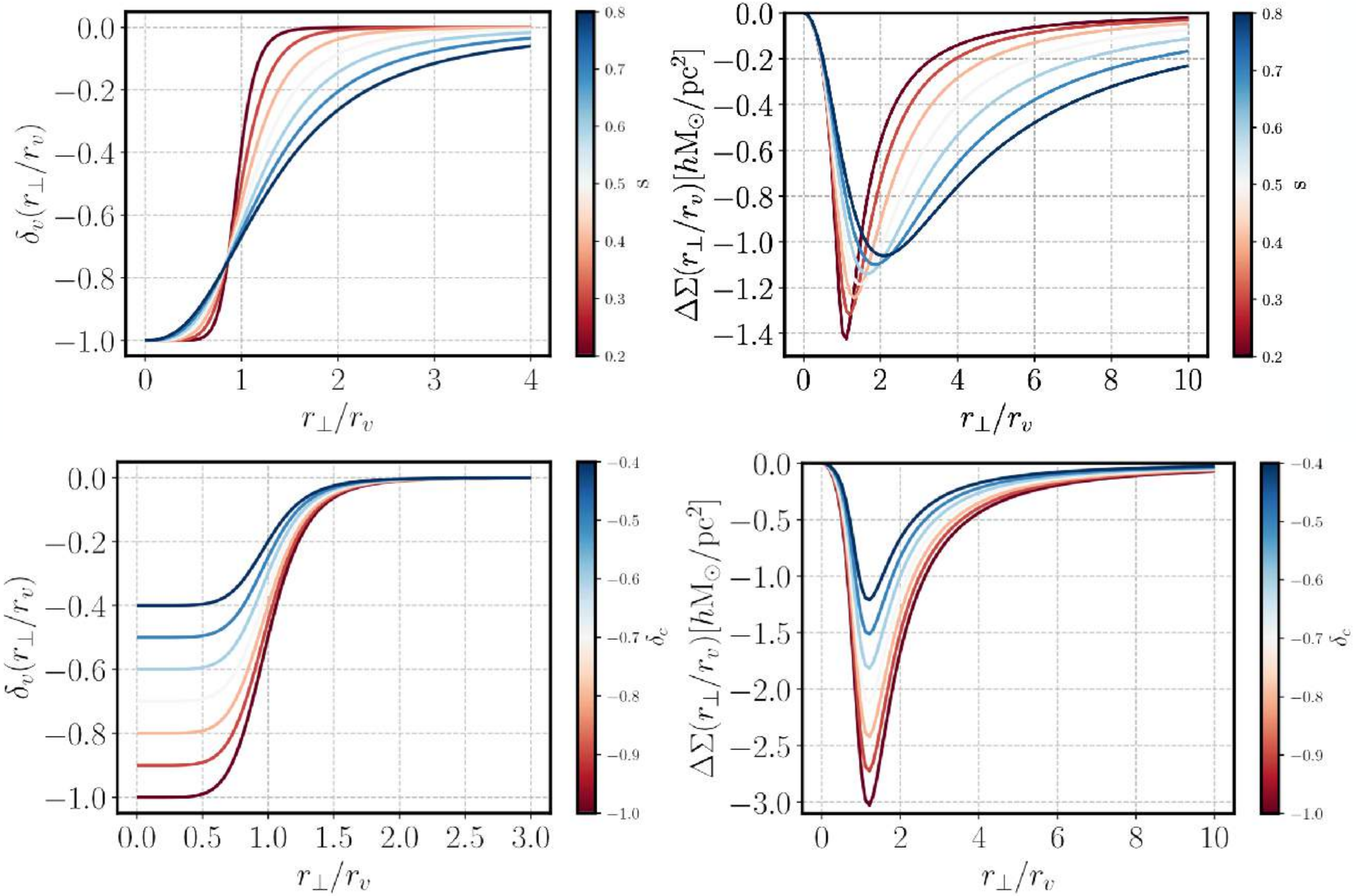
# How To Void Lensing?



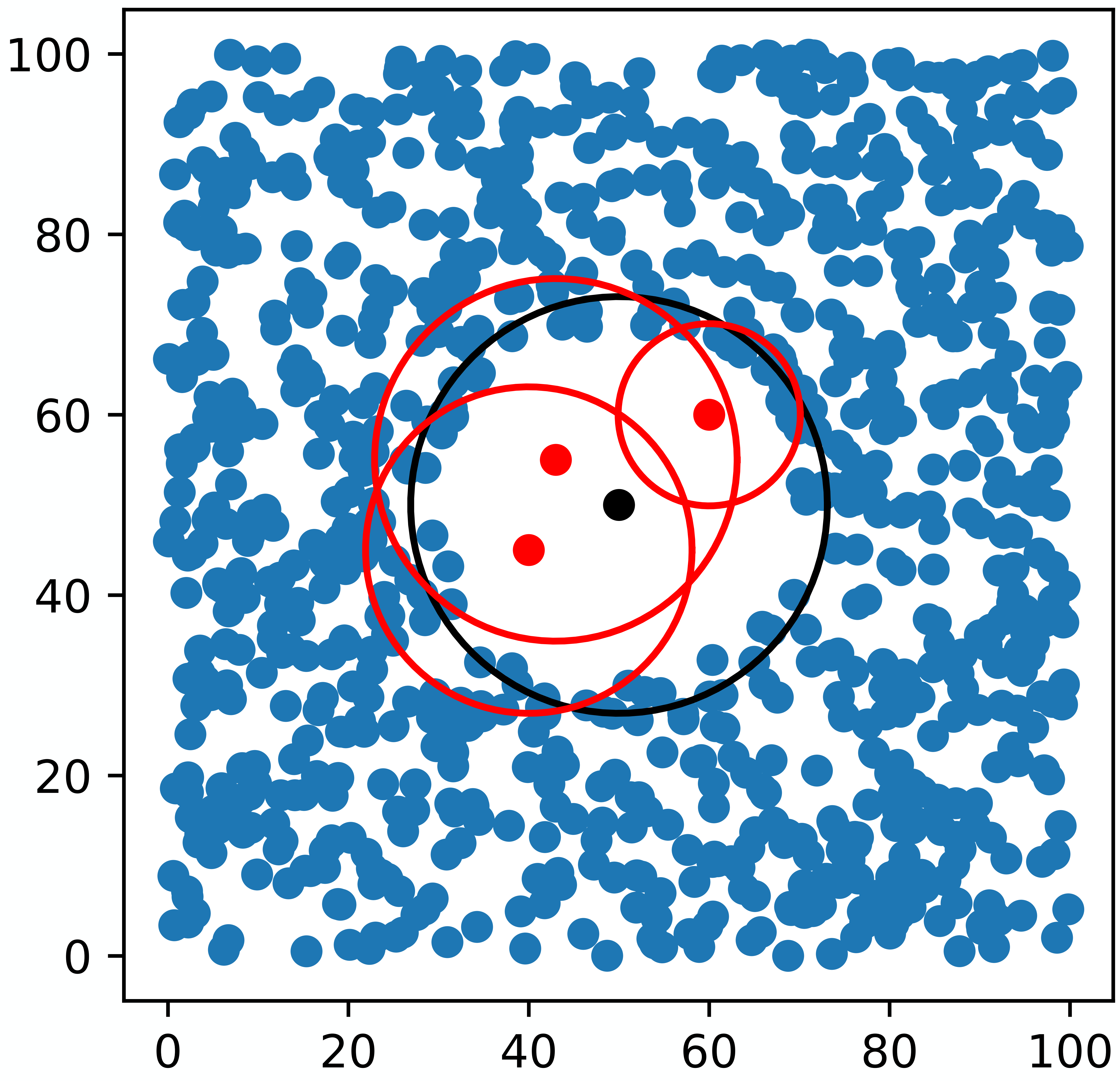

Gadget simulation (Spergel)

# What Voids Must Be

$$\delta_v(r|R_v) \equiv \frac{\rho_v\left(r \mid R_v\right)}{\bar{\rho}_m} - 1 = |\delta_c| \left\{ \frac{1}{2}\left[1+\tanh\left(\frac{y-y_0}{s\left(R_v\right)}\right)\right] - 1 \right\}$$

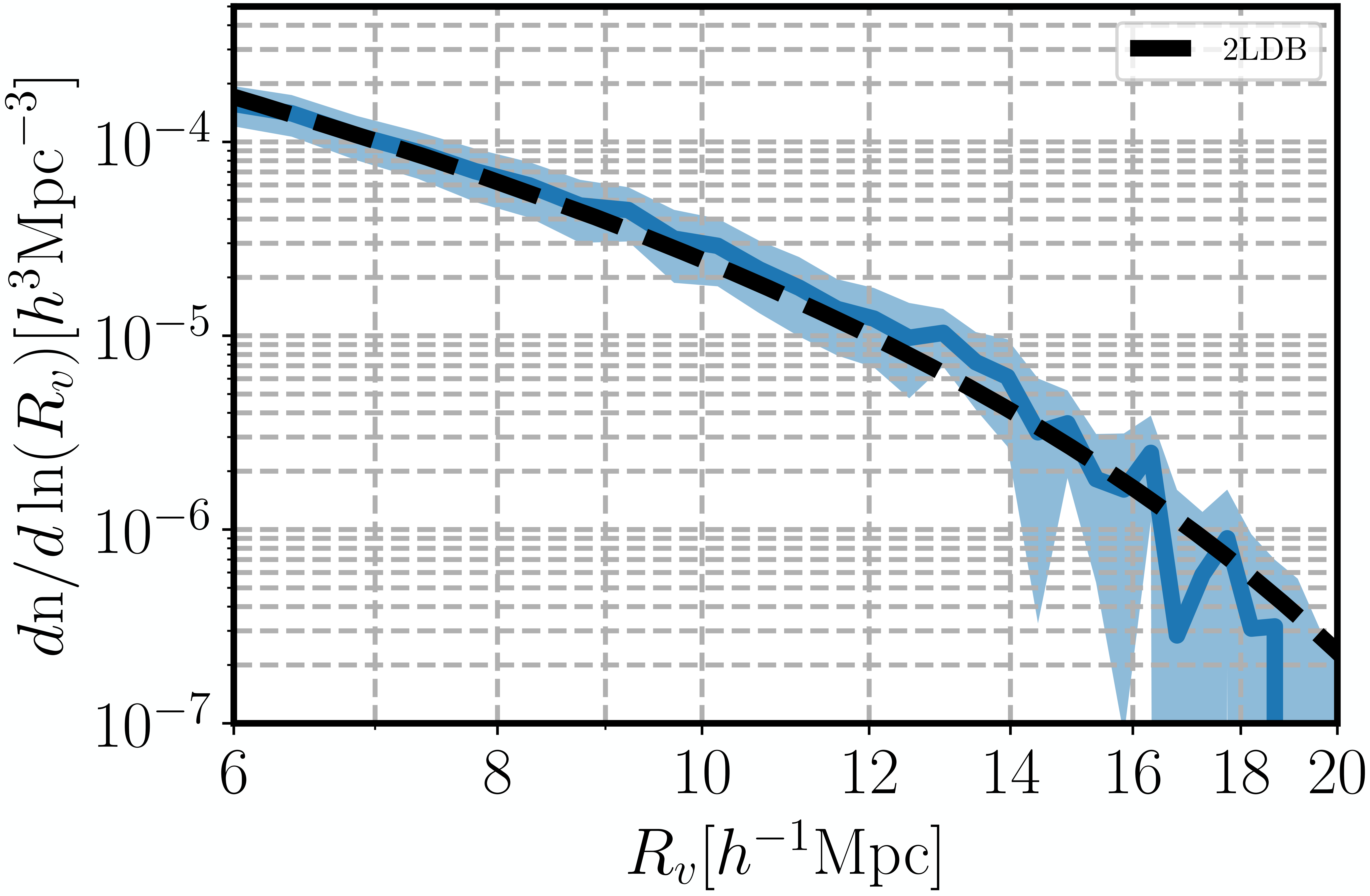


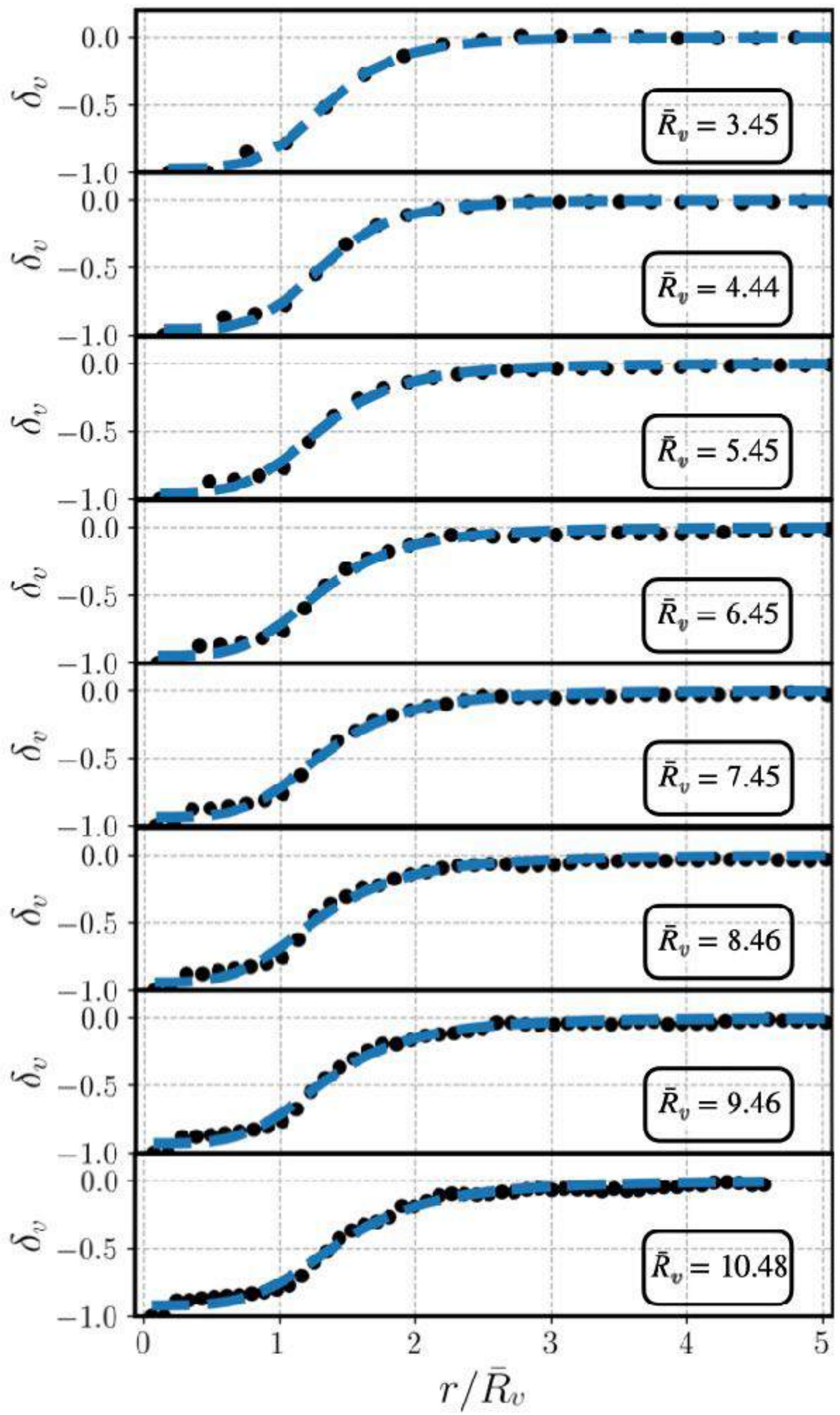
# Toy Optimum Centering Void Finder



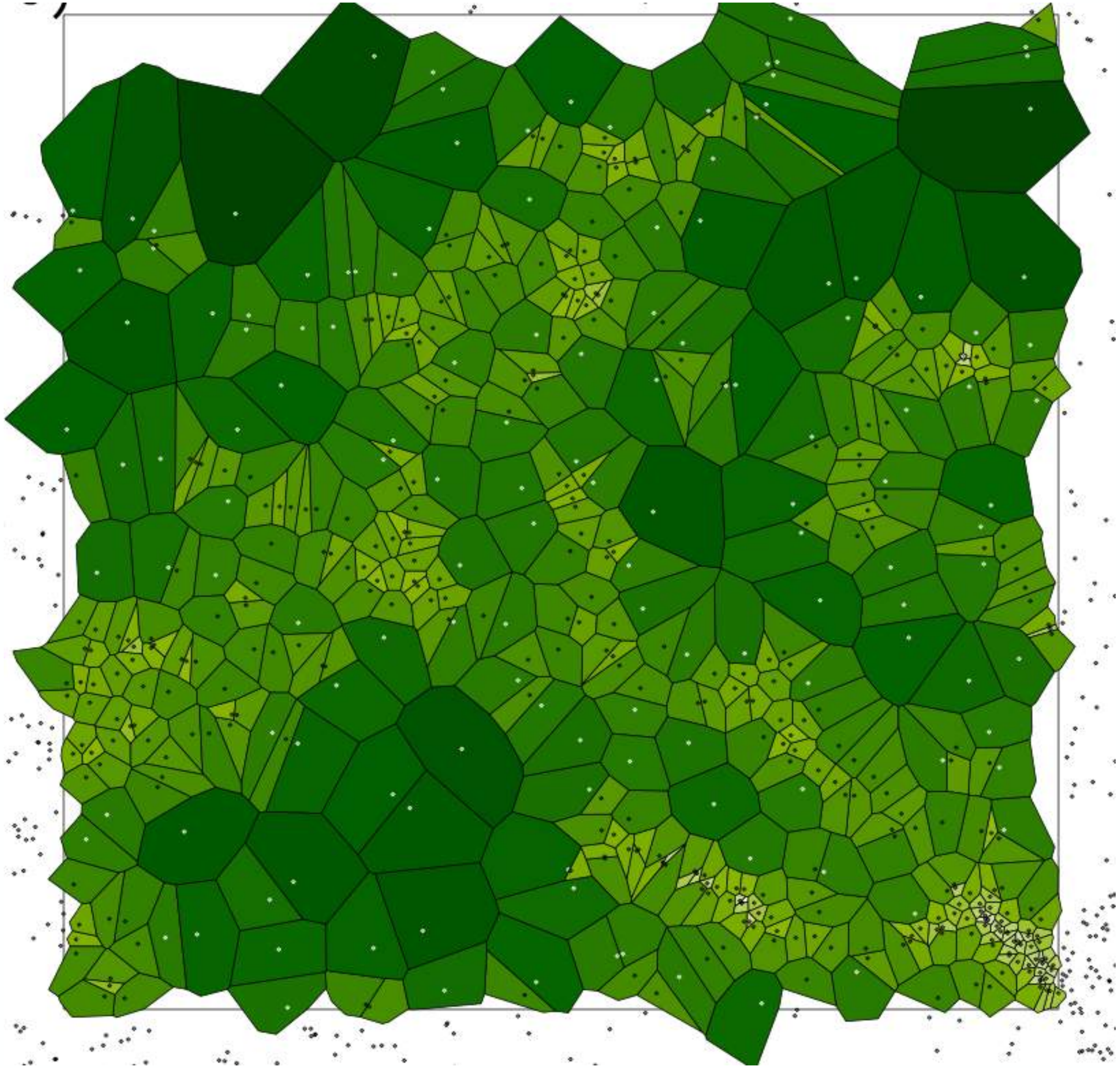
# Everything Leads to OCVF

# Theory X Simulation (3D)



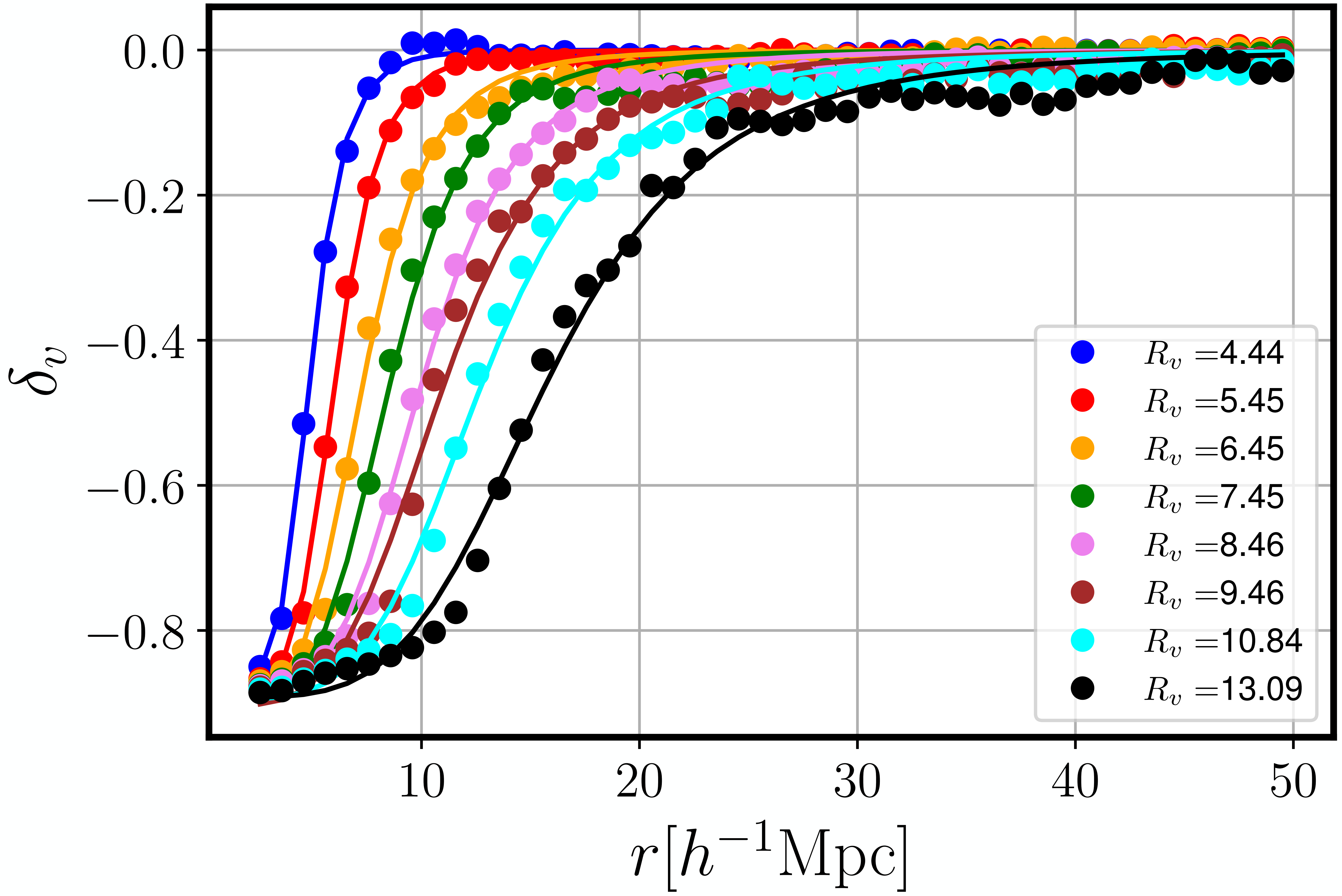
# ZOBOV Voids



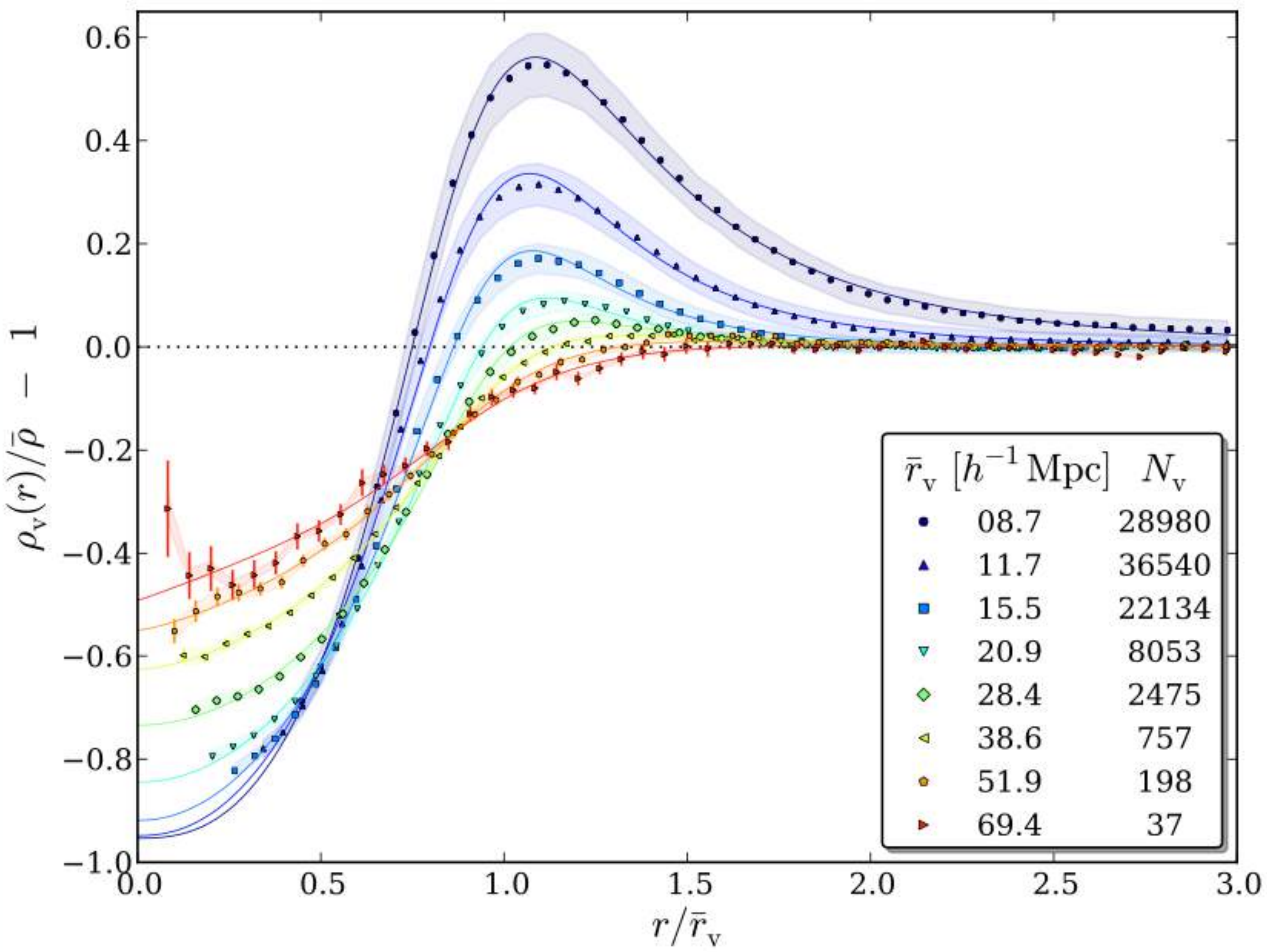
Neyrinck (2008)

# Comparison With Literature (3D) – Mark C. Neyrinck (2004)

**OCVF 3D**

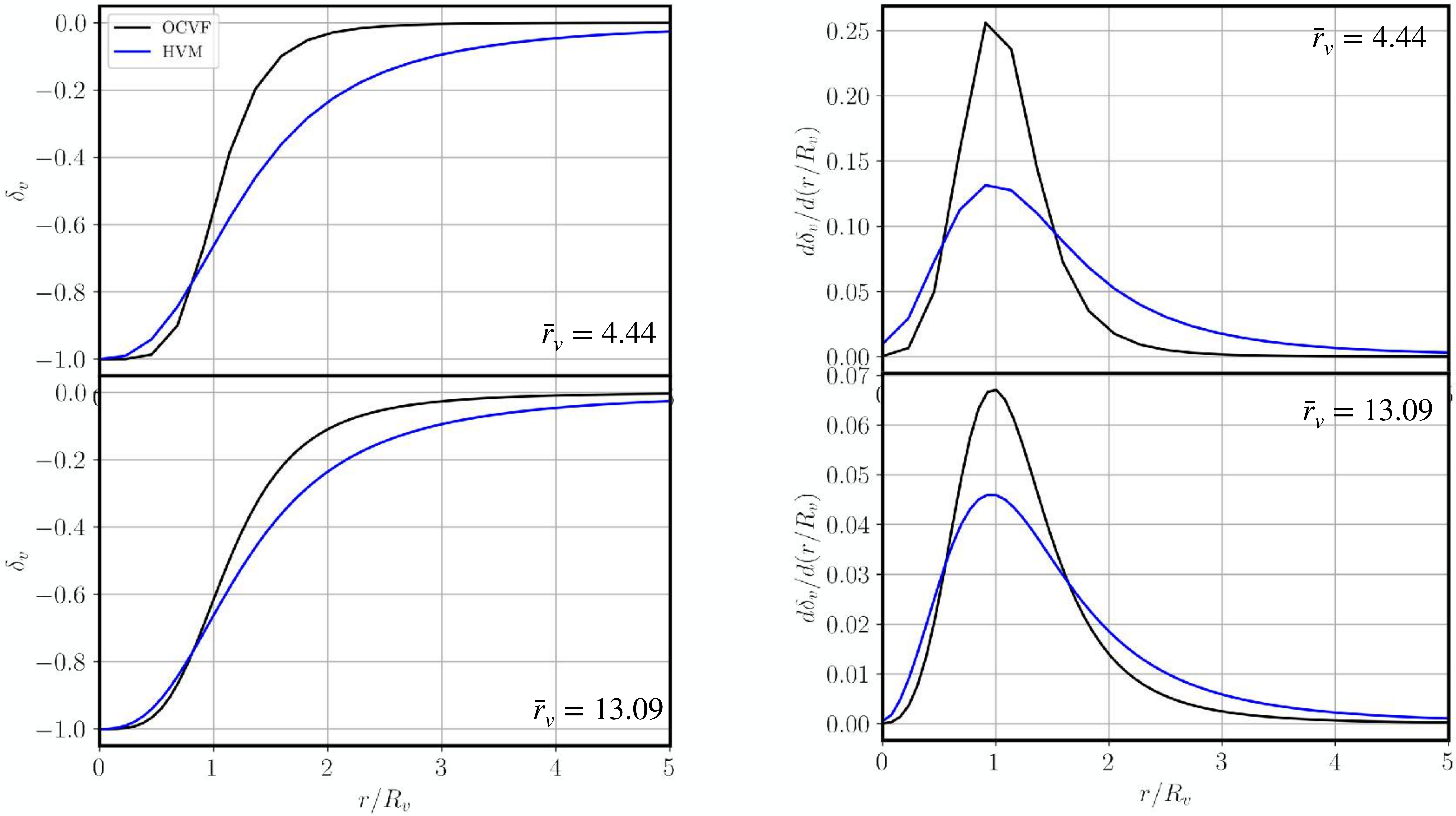



**ZOBOV**

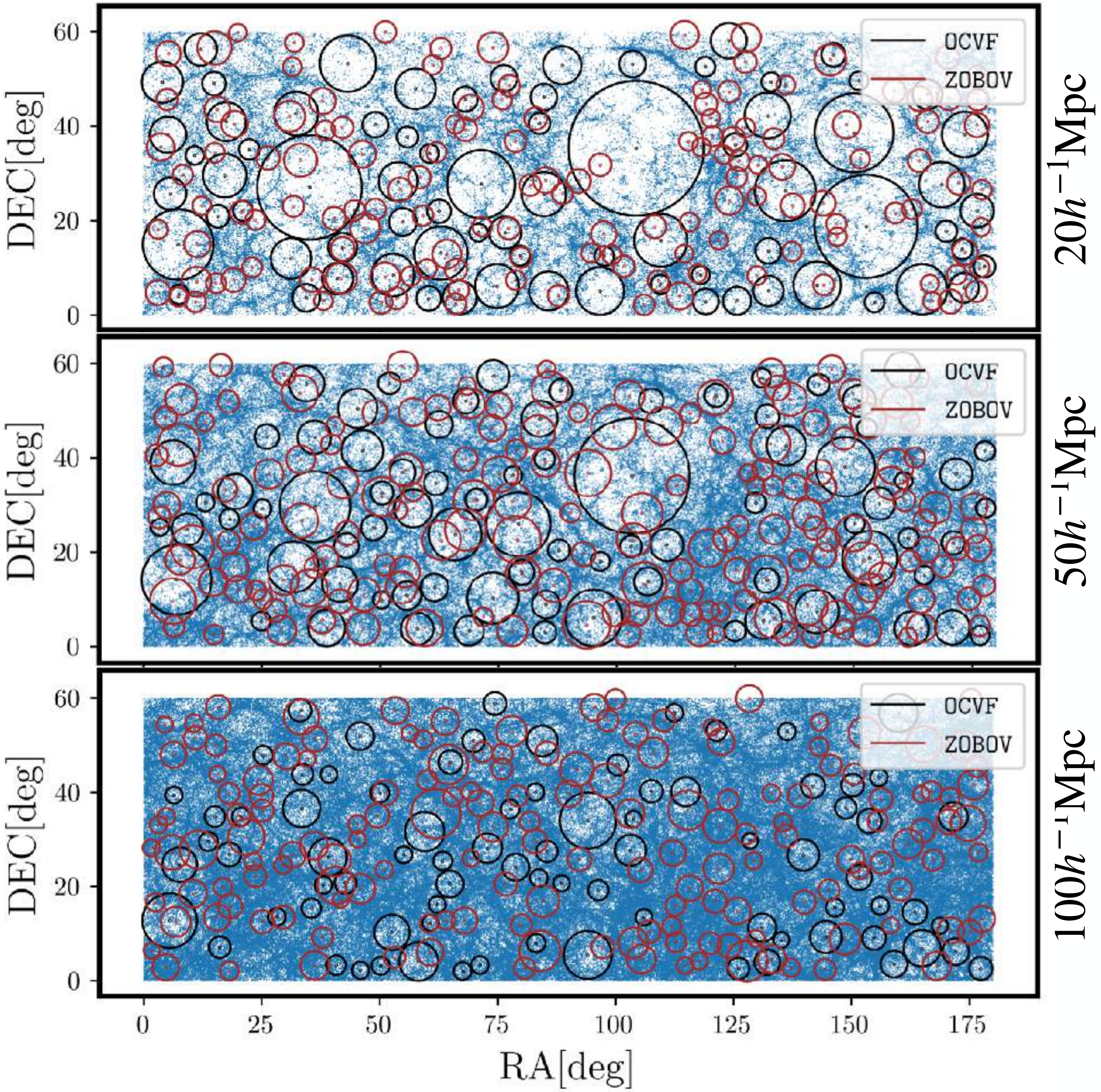


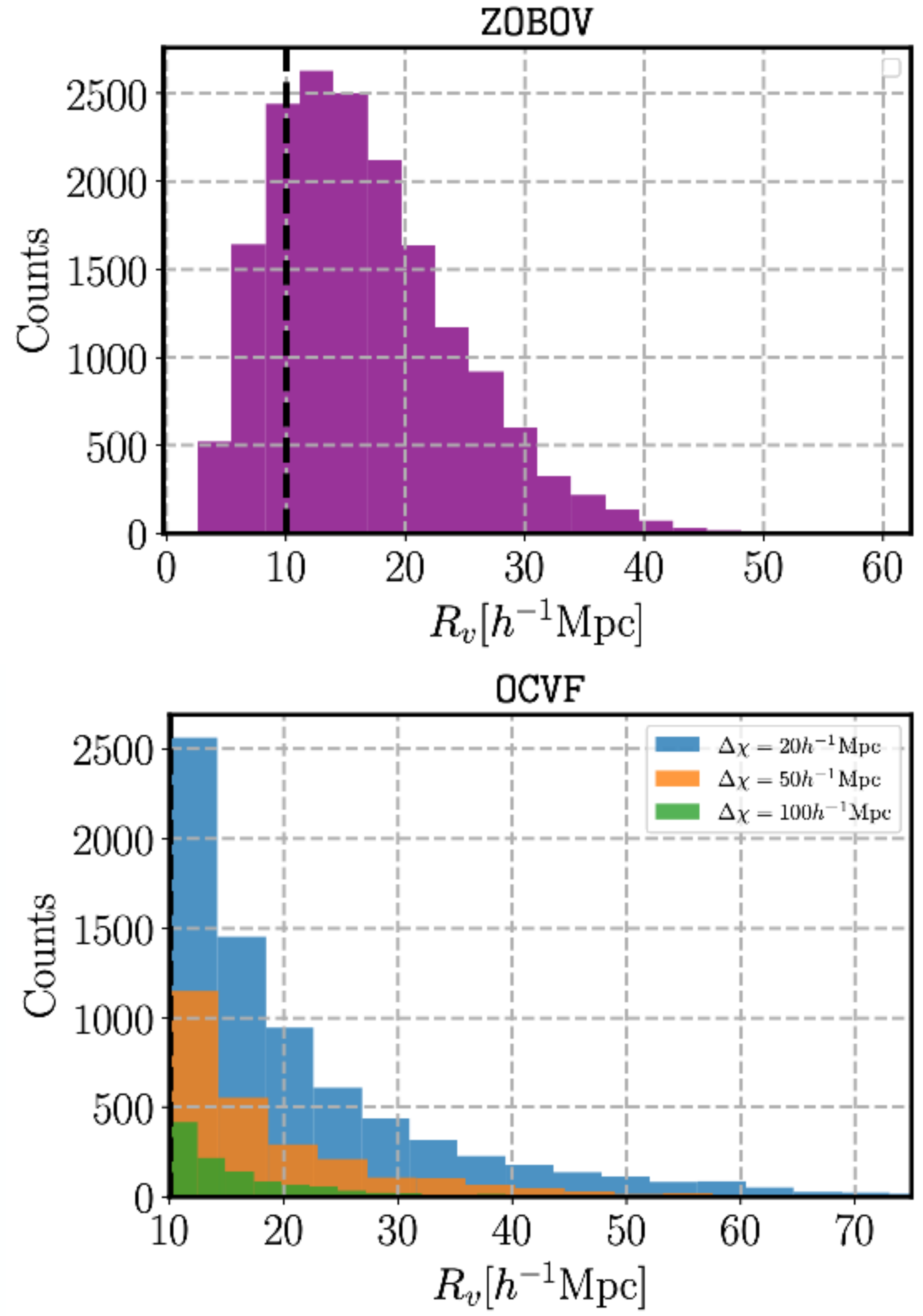

**Hamaus et al (2014)**

# Comparison With Literature (3D) – Voivodic Et AL. (2020)

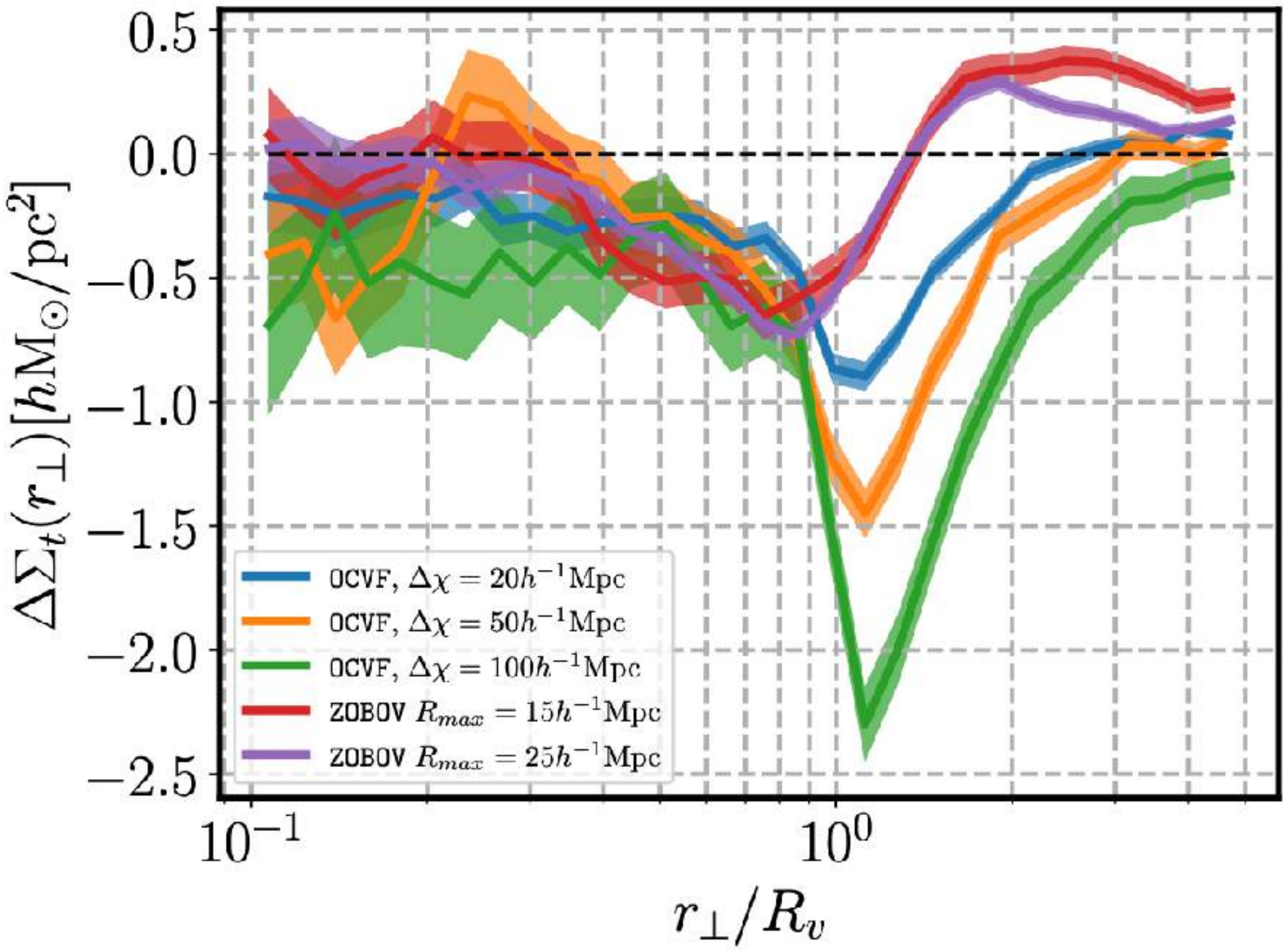


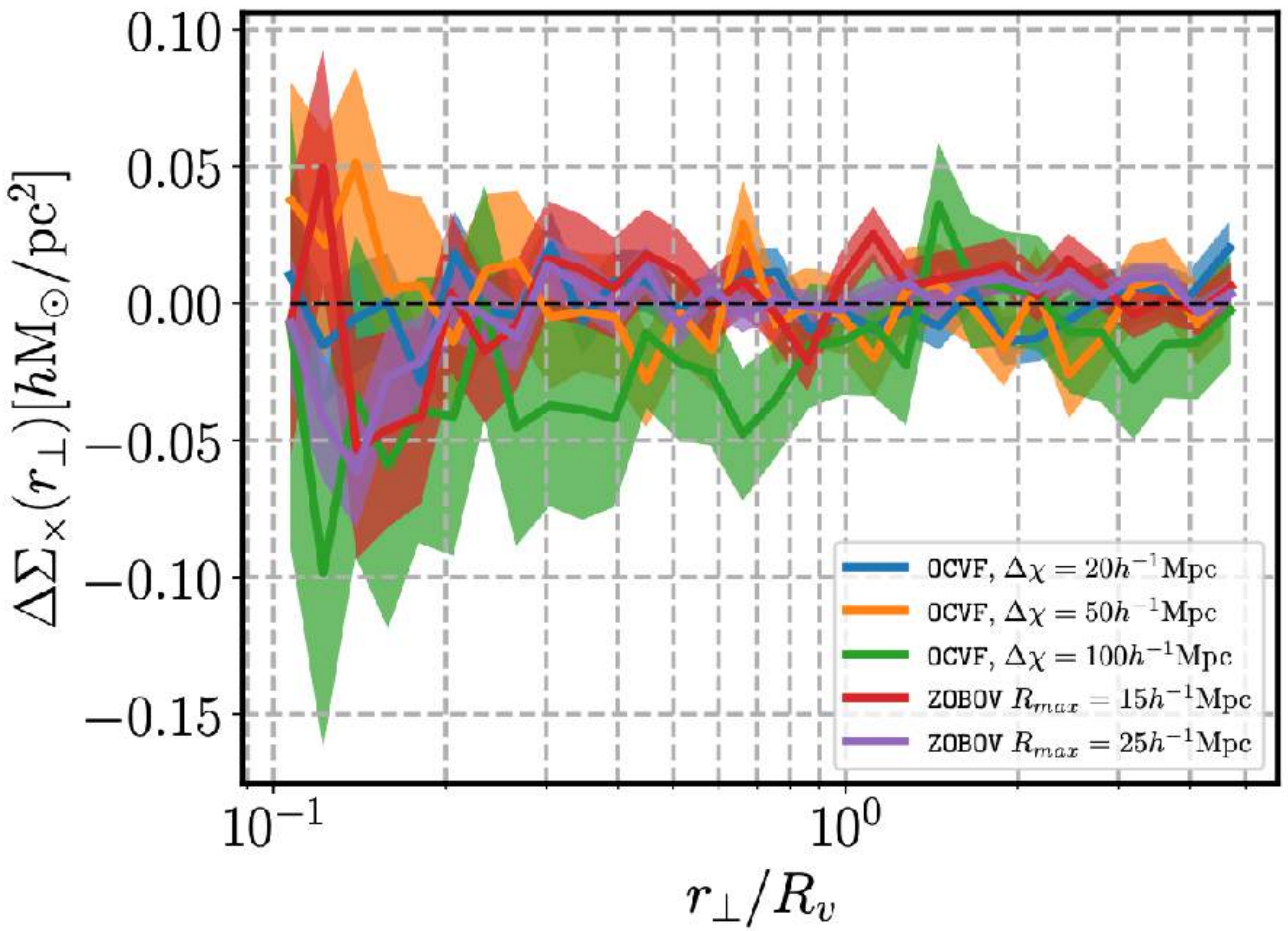
# Void-Lensing Measurements Visualisation ( $\sim 10^3 deg^2, 0.1 < z < 0.3$)



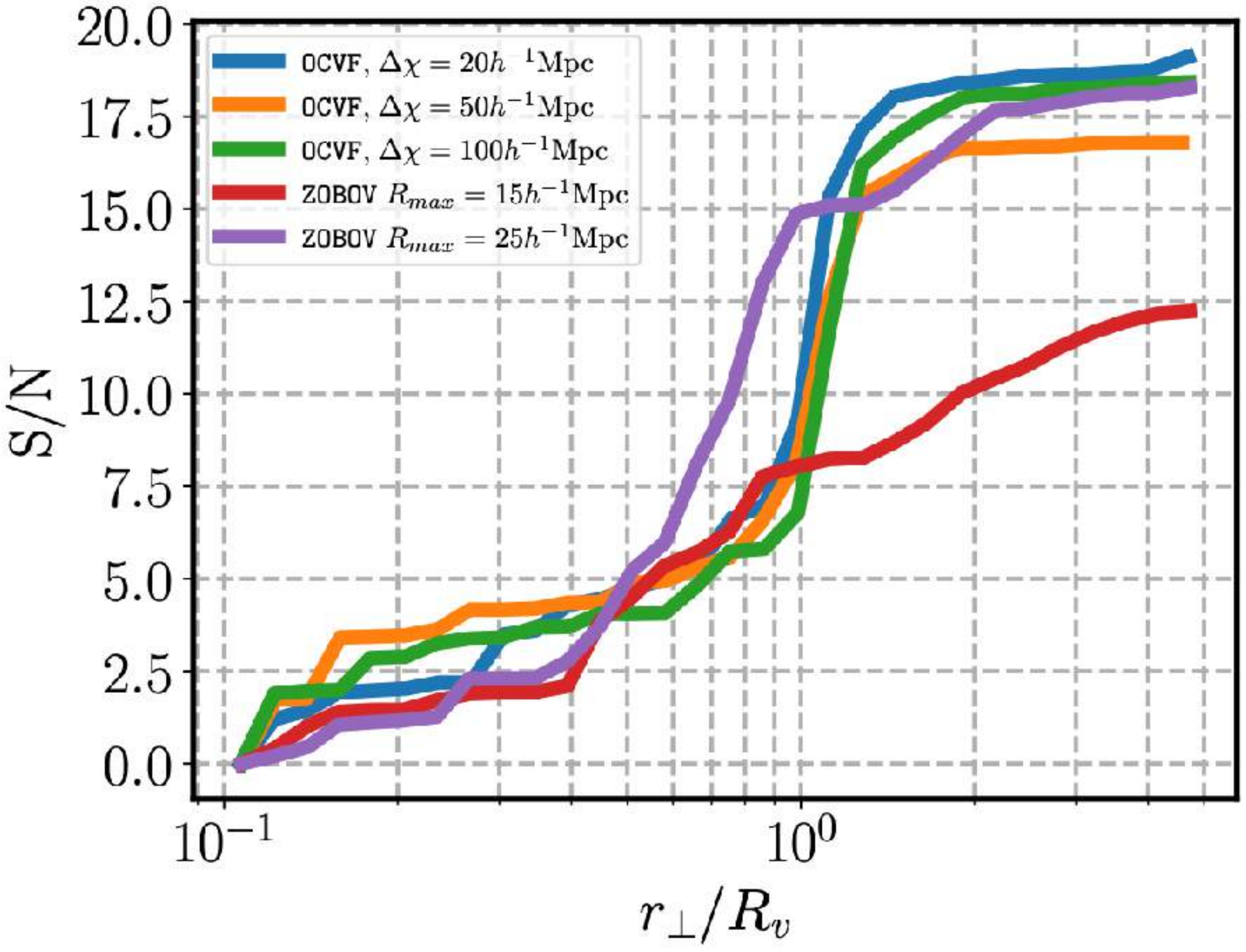



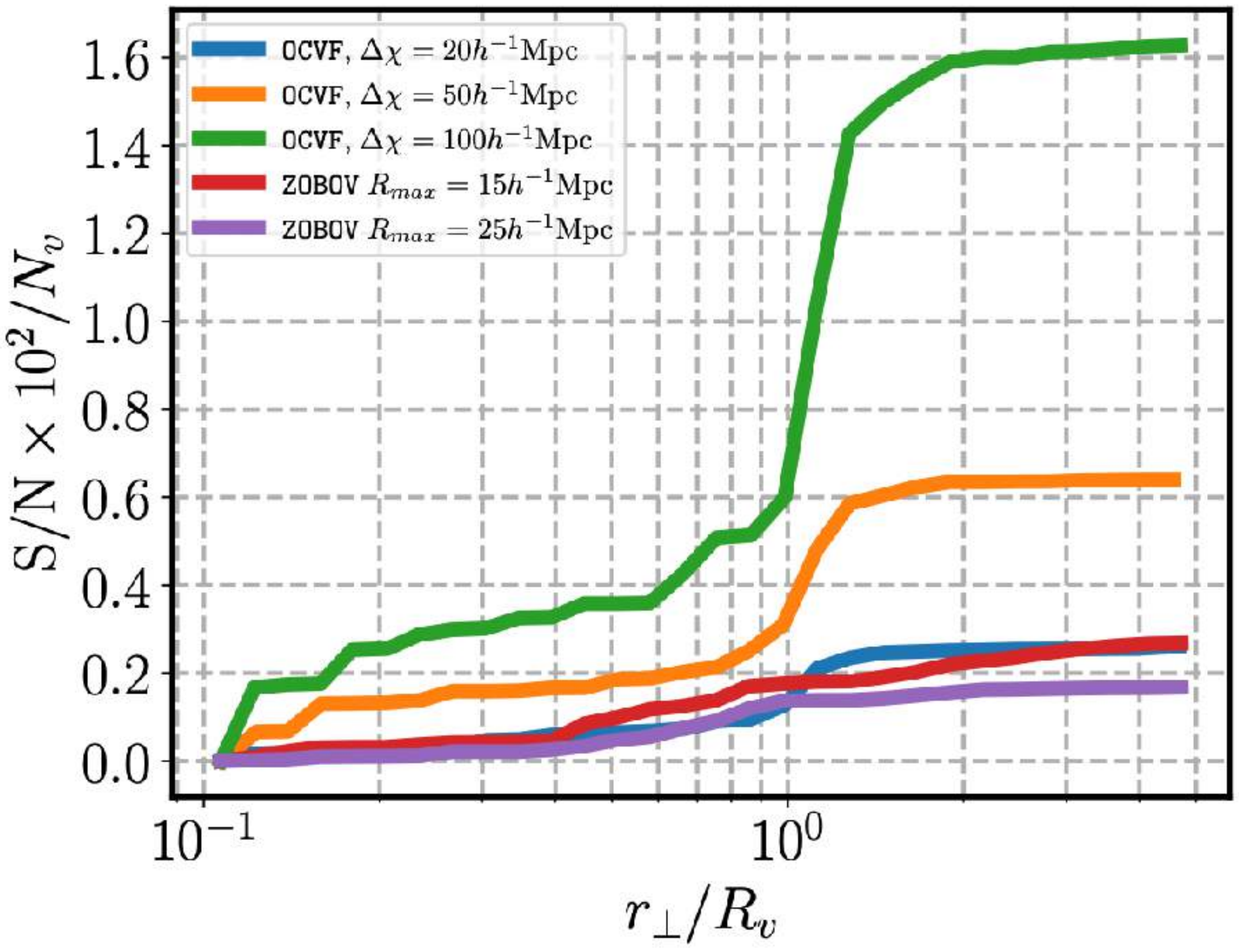
# Void-Lensing Measurements



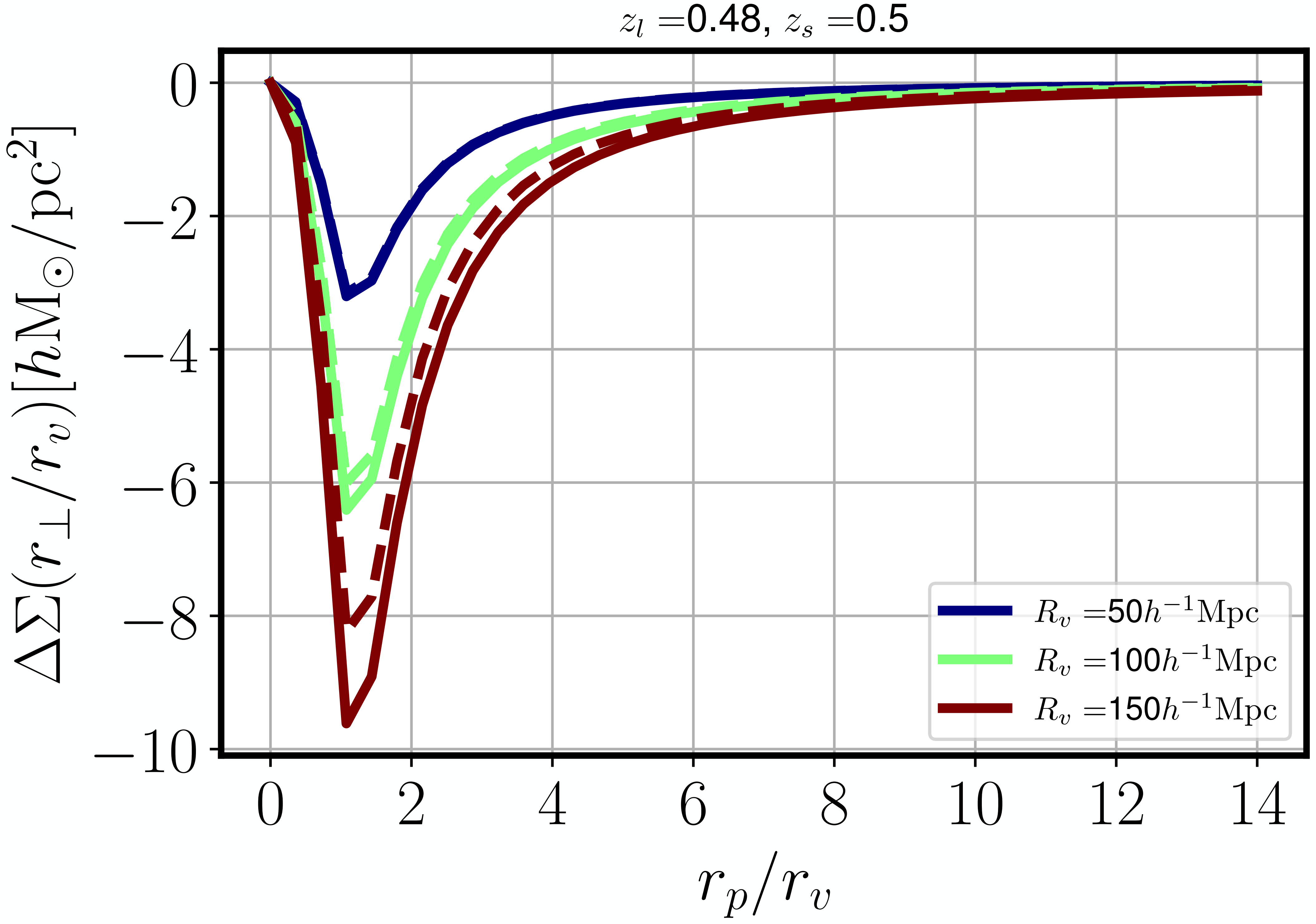
# Void-Lensing Measurements – S/N

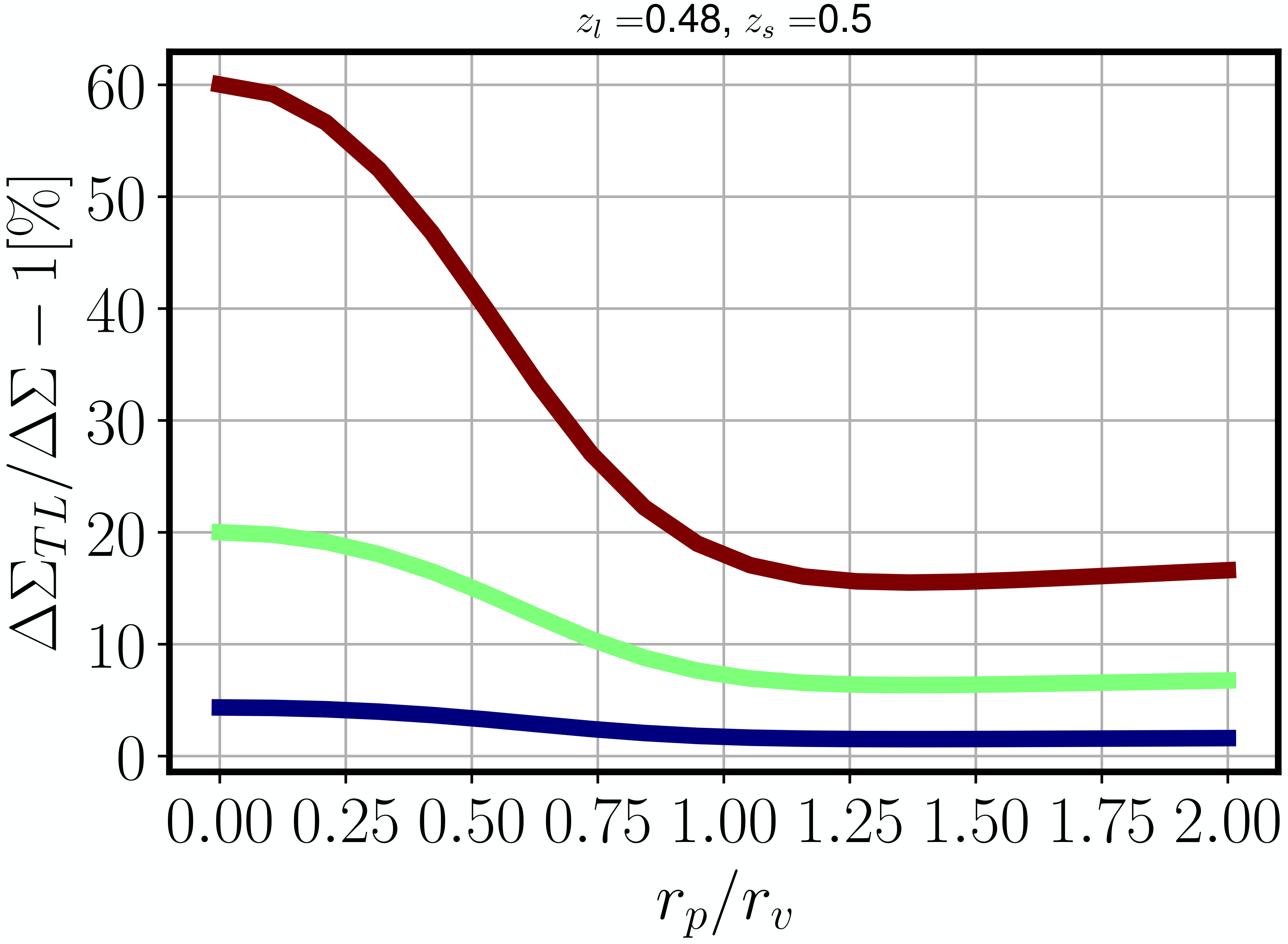


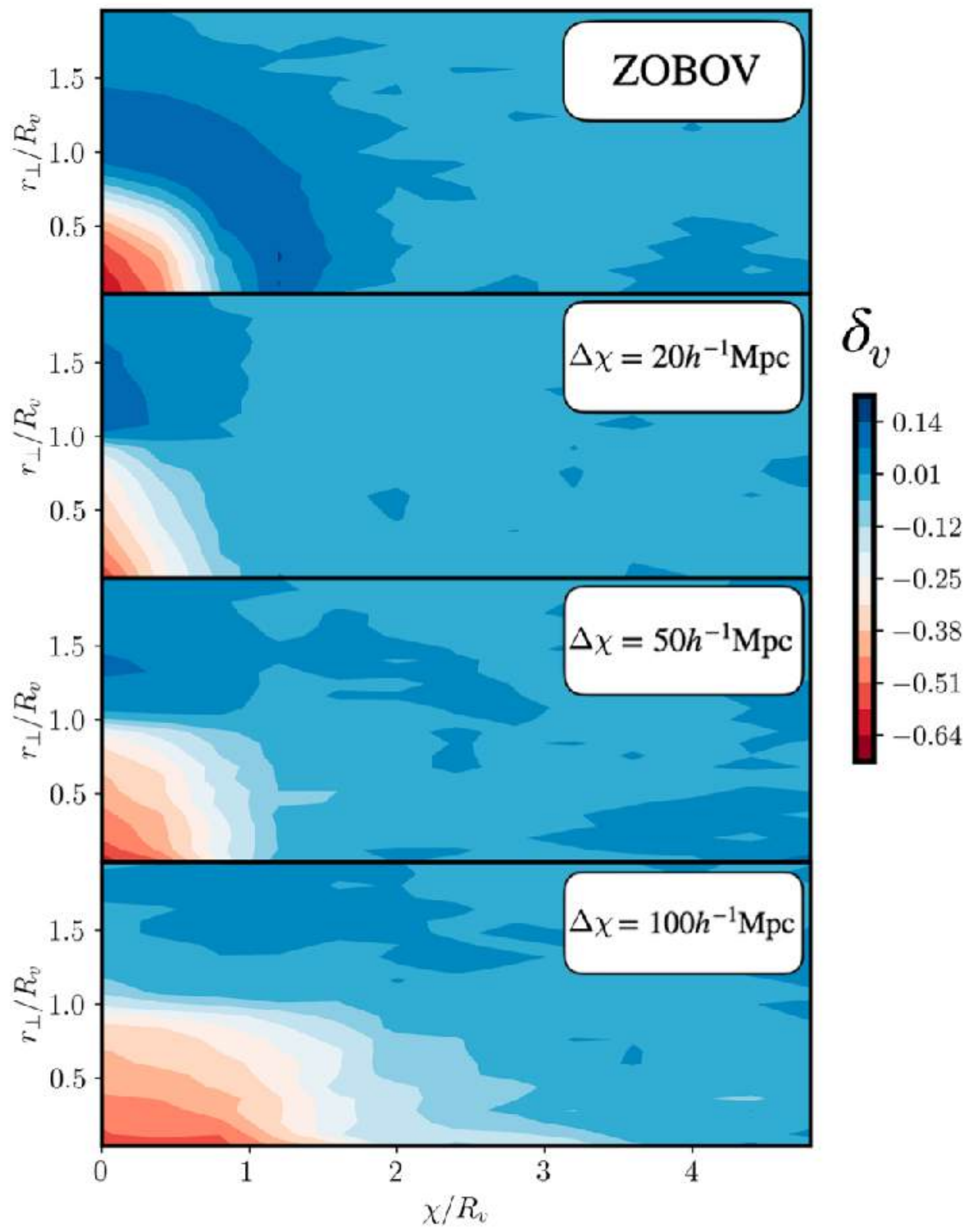
# The Thin-Lens Approximation

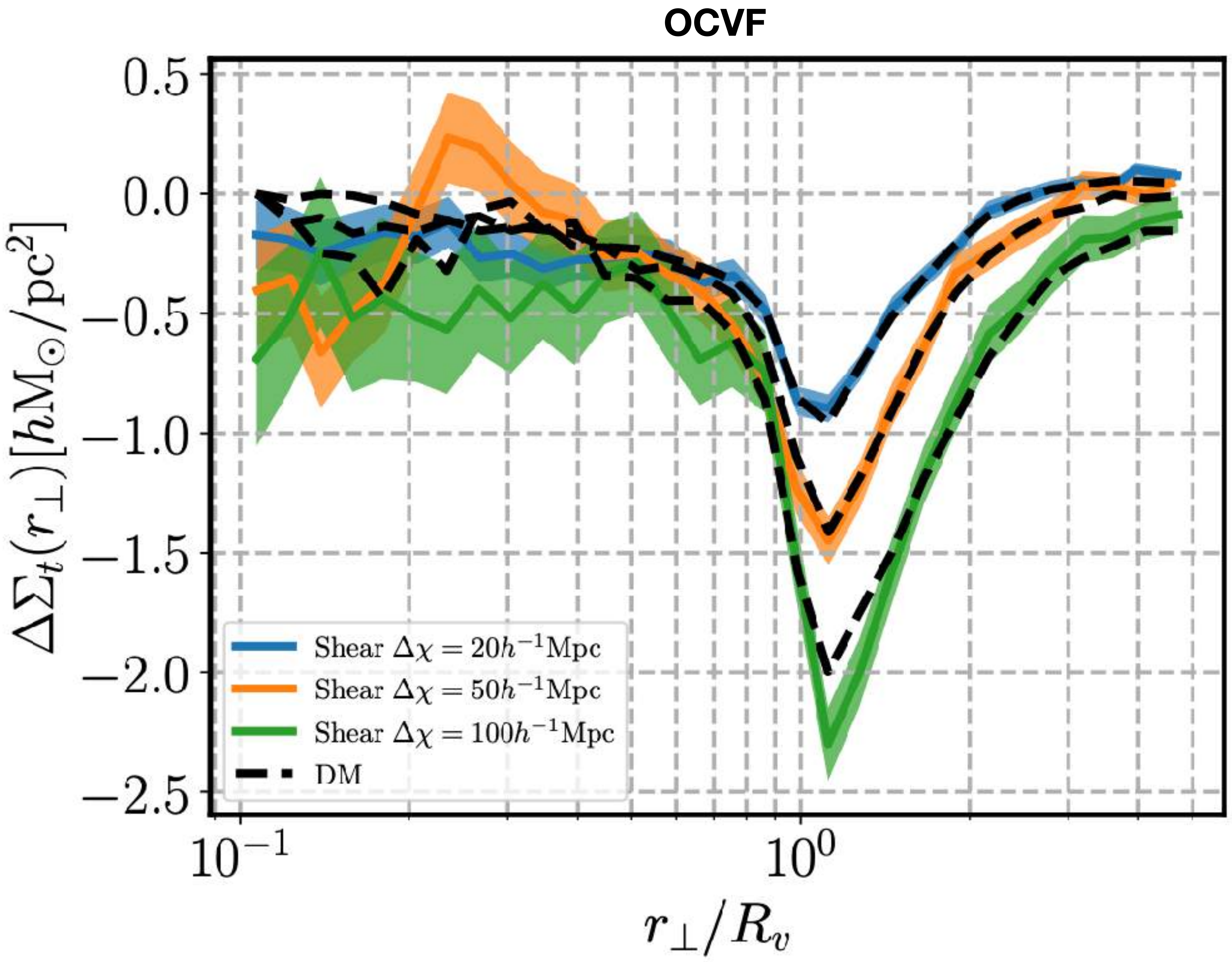
$$\kappa(\boldsymbol{\theta}) = \frac{4\pi G}{c^2}\frac{\chi_1\chi_{1s}}{\chi_s}\int_{\chi_1-\Delta\chi/2}^{\chi_1+\Delta\chi/2} \mathrm{d}\chi\bar{\rho}\delta(\chi\boldsymbol{\theta},\chi) = \frac{\Sigma(\boldsymbol{\theta})}{\Sigma_{cr}}$$



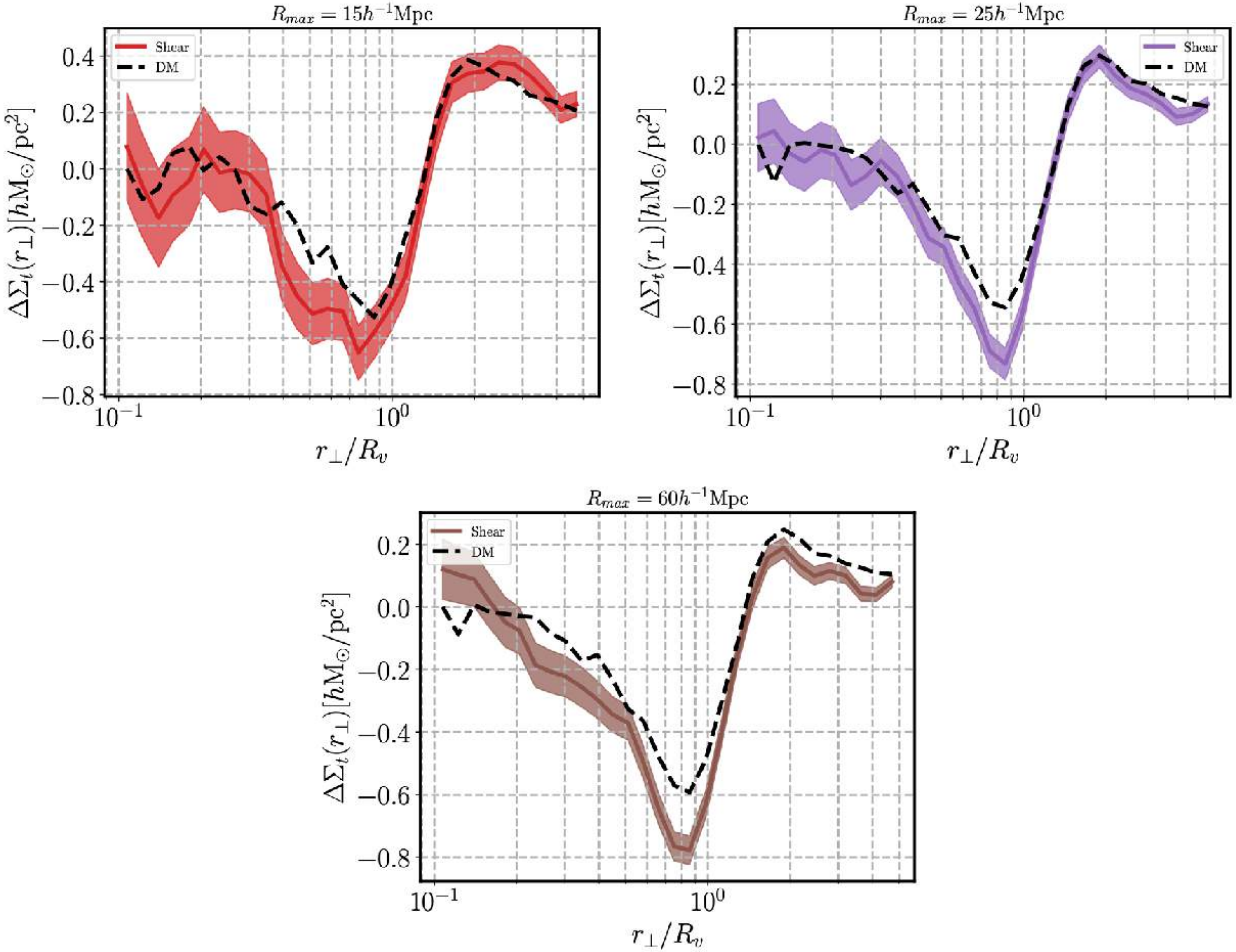
# DM Profile X VL Profile



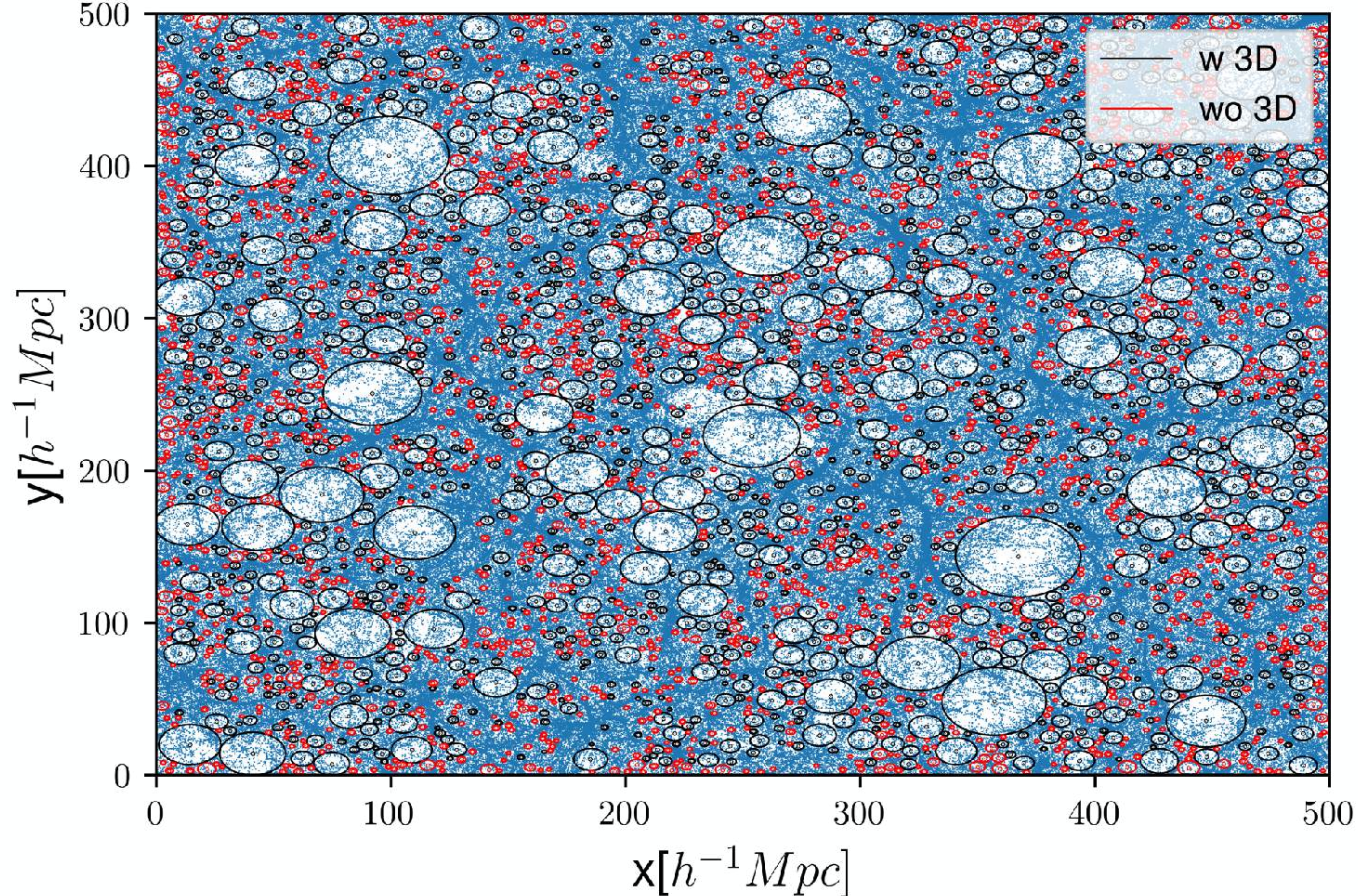
# DM Profile X VL Profile

**ZOBOV**

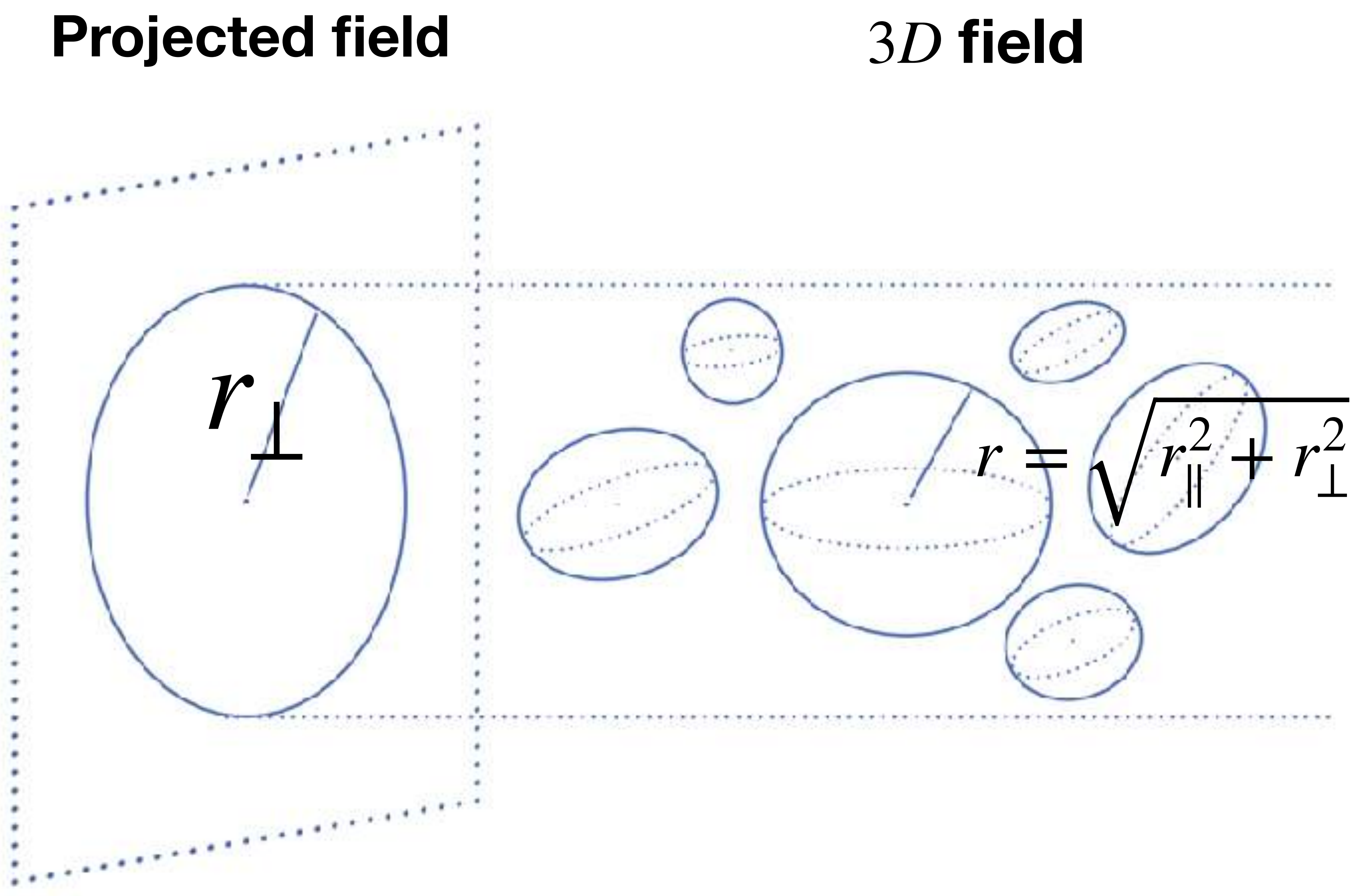


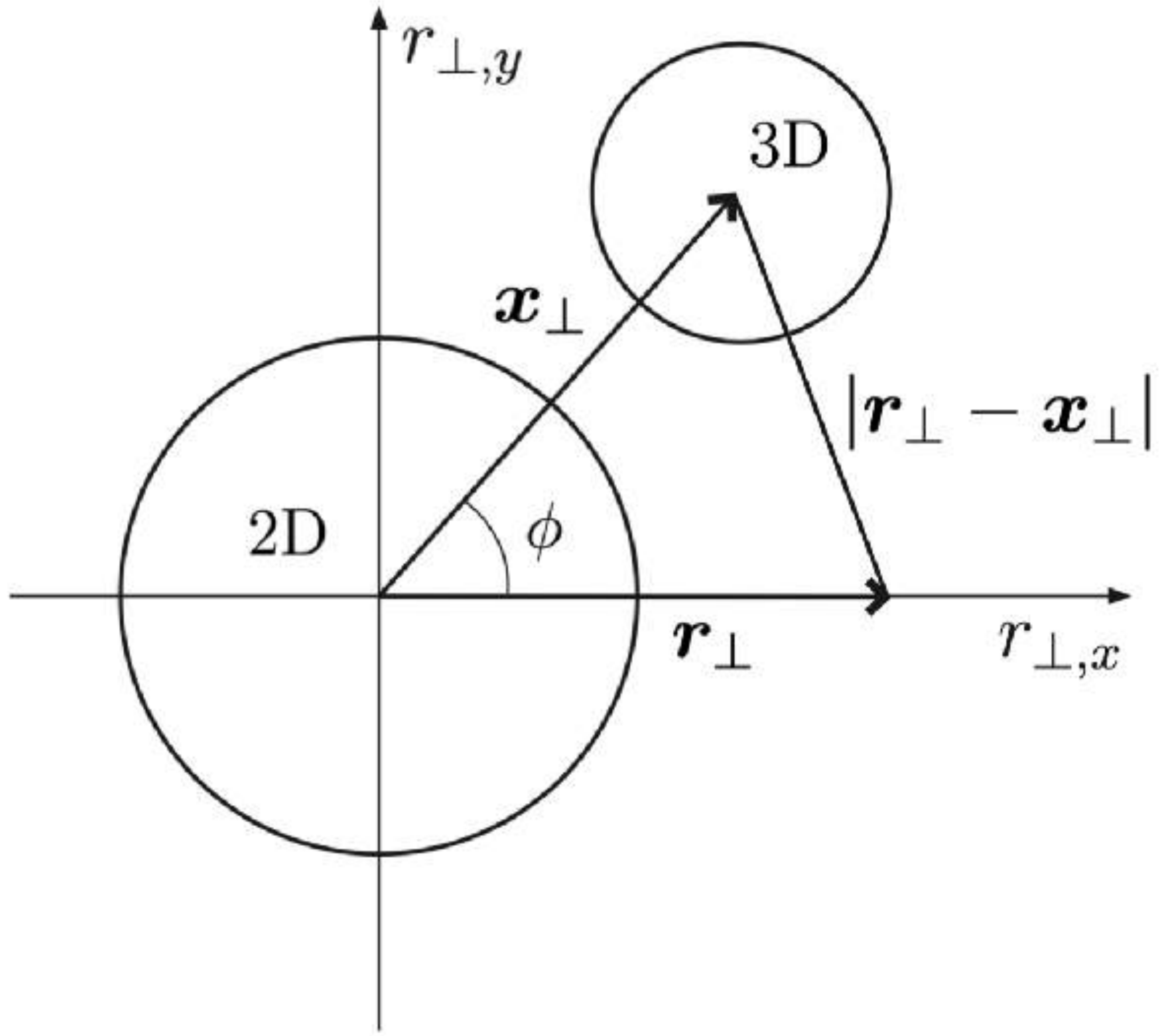
# The Void-Lensing Model
# Or
# 2D-3D Connection

# 2D-3D Connection



# The Void-Lensing Model




$$\Sigma(r_\perp \,|\, R_{2D}, \Delta_{2D}, \Delta_{3D}) = \mathscr{F}[\delta_{3D}(R_{3D}, \Delta_{3D}) \,|\, R_{2D}, \Delta_{2D}]$$

$$\Sigma(r_\perp \,|\, R_{2D}, \Delta_{2D}, \Delta_{3D}) = \frac{1}{N}\int dR_{3D}\,\frac{dn_v}{dR_{3D}}(R_{3D} \,|\, \Delta_{3D}) \times \int dx_\perp d\phi\, P(x_\perp \,|\, R_{3D}, R_{2D}, \Delta_{3D}, \Delta_{2D}) \times \int dr_\parallel \delta_{3D}(|\boldsymbol{r}_\perp - \boldsymbol{x}_\perp| \,|\, R_{3D}, \Delta_{3D})$$

$$= \int dr_\parallel \delta^{eff}(r_\perp, r_\parallel)$$

$$\Rightarrow \Delta\Sigma(r_\perp) = \bar{\Sigma}( < r_\perp) - \Sigma(r_\perp)$$

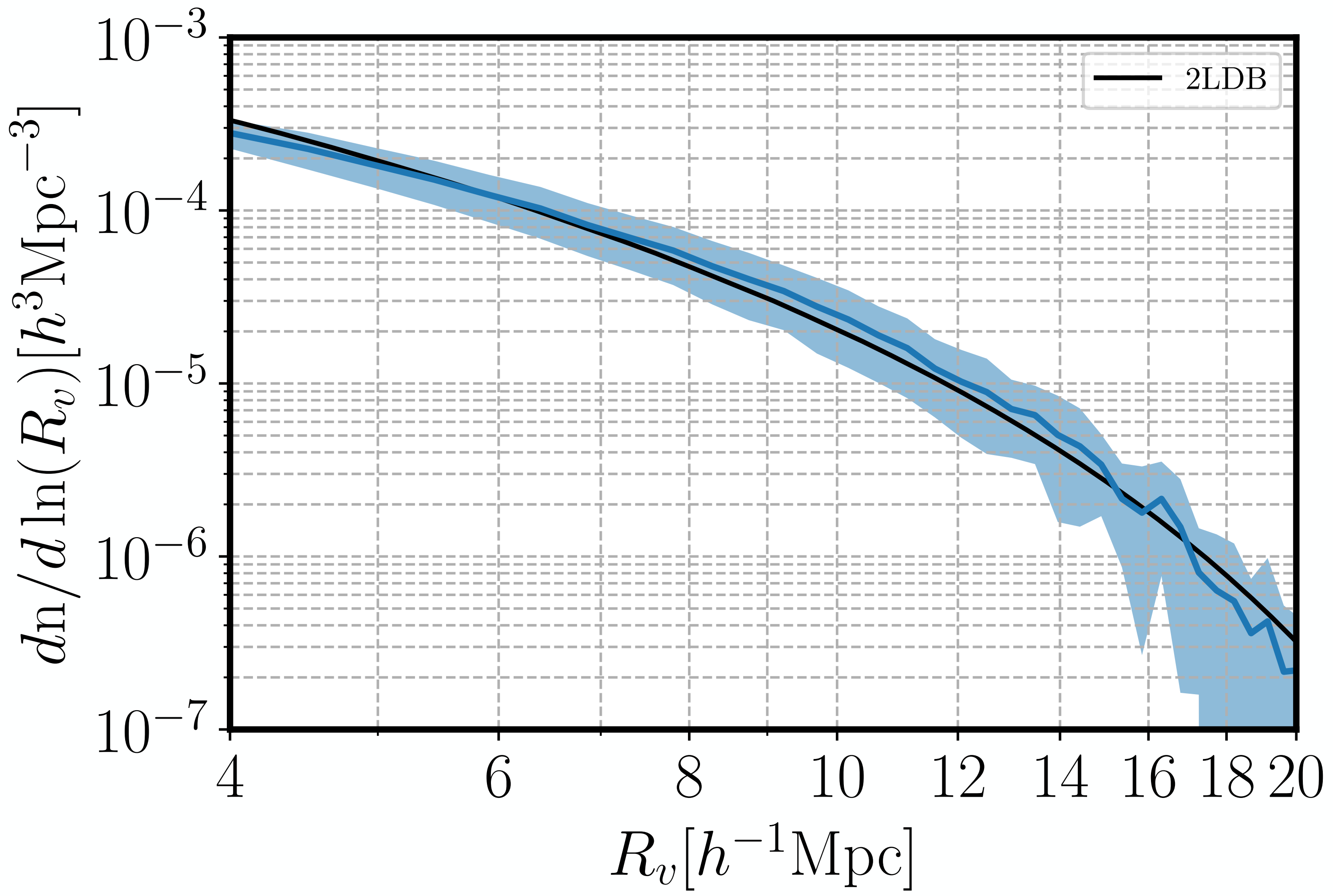
# The Void-Lensing Model

$$\Sigma(r_\perp | R_{2D}, \Delta_{2D}, \Delta_{3D}) = \frac{1}{N}\int dR_{3D}\, \frac{dn_v}{dR_{3D}}(R_{3D}|\Delta_{3D}) \times \int dx_\perp d\phi\, P(x_\perp | R_{3D}, R_{2D}, \Delta_{3D}, \Delta_{2D}) \times \int dr_\| \delta_{3D}(|\boldsymbol{r}_\perp - \boldsymbol{x}_\perp| | R_{3D}, \Delta_{3D})$$

$$\simeq$$

$$\Sigma(r_\perp | R_{2D}) = \int d\ln R_{3D} \boxed{\frac{dn_v}{d\ln R_{3D}}} \int dx_\perp d\phi \xi_{2D,3D}(x_\perp) \int dr_\| \,\delta_{3D}(|\boldsymbol{r}_\perp - \boldsymbol{x}_\perp| | R_{3D})$$

$$\frac{dn_v}{d\ln R} = \frac{f(\sigma)}{V(R)} \frac{d\ln\sigma^{-1}}{d\ln R}$$ , **where** $$\sigma^2(R) \equiv \int \frac{dk}{2\pi^2} k^2 P^L_{mm}(k) | \tilde{W}(k | R) |^2$$



# The Void-Lensing Model

$$\Sigma(r_\perp | R_{2D}, \Delta_{2D}, \Delta_{3D}) = \frac{1}{N} \int dR_{3D} \frac{dn_v}{dR_{3D}} (R_{3D} | \Delta_{3D}) \times \int dx_\perp d\phi \, P(x_\perp | R_{3D}, R_{2D}, \Delta_{3D}, \Delta_{2D}) \times \int dr_\parallel \delta_{3D}(|\boldsymbol{r}_\perp - \boldsymbol{x}_\perp| | R_{3D}, \Delta_{3D})$$

$$\simeq$$

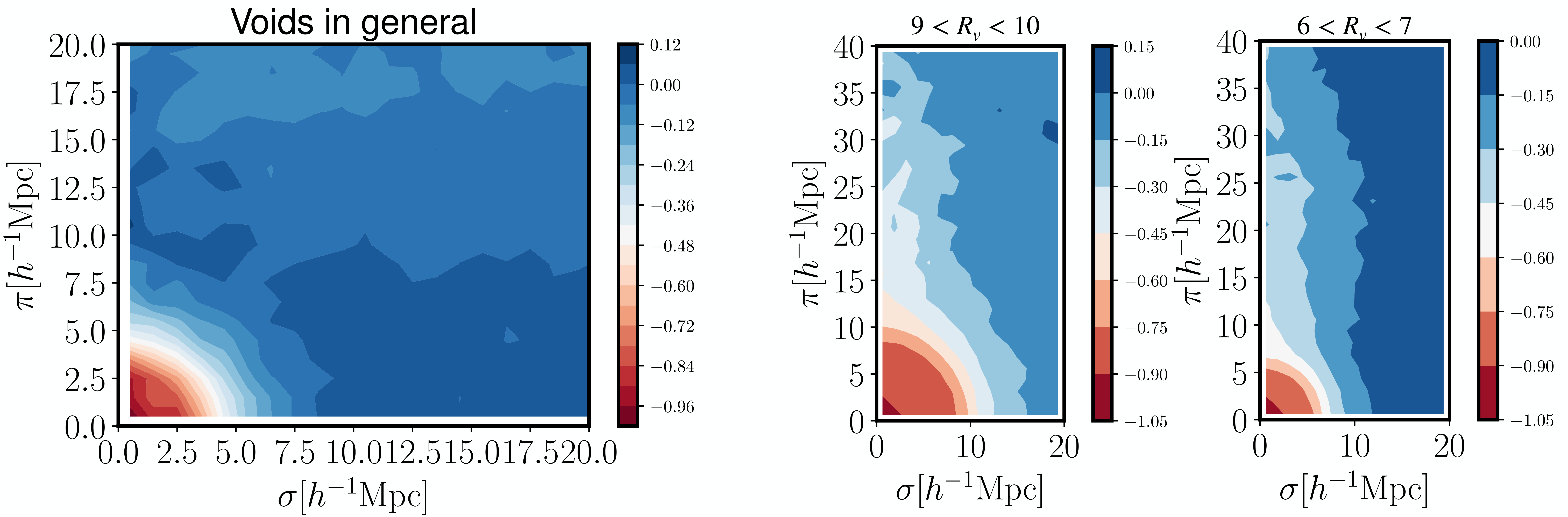
$$\Sigma(r_\perp | R_{2D}) = \int d\ln R_{3D} \frac{dn_v}{d\ln R_{3D}} \int dx_\perp d\phi \boxed{\xi_{2D,3D}(x_\perp)} \int dr_\parallel \, \delta_{3D}(|\boldsymbol{r}_\perp - \boldsymbol{x}_\perp| | R_{3D})$$

# The Void-Lensing Model

$$\Sigma(r_\perp | R_{2D}, \Delta_{2D}, \Delta_{3D}) = \frac{1}{N}\int dR_{3D}\,\frac{dn_v}{dR_{3D}}(R_{3D}|\Delta_{3D}) \times \int dx_\perp d\phi\, P(x_\perp | R_{3D}, R_{2D}, \Delta_{3D}, \Delta_{2D}) \times \int dr_\parallel \delta_{3D}(|\boldsymbol{r}_\perp - \boldsymbol{x}_\perp| | R_{3D}, \Delta_{3D})$$

$$\simeq$$

$$\Sigma(r_\perp | R_{2D}) = \int d\ln R_{3D}\,\frac{dn_v}{d\ln R_{3D}} \int dx_\perp d\phi\, \xi_{2D,3D}(x_\perp) \int dr_\parallel \boxed{\delta_{3D}(|\boldsymbol{r}_\perp - \boldsymbol{x}_\perp| | R_{3D})}$$

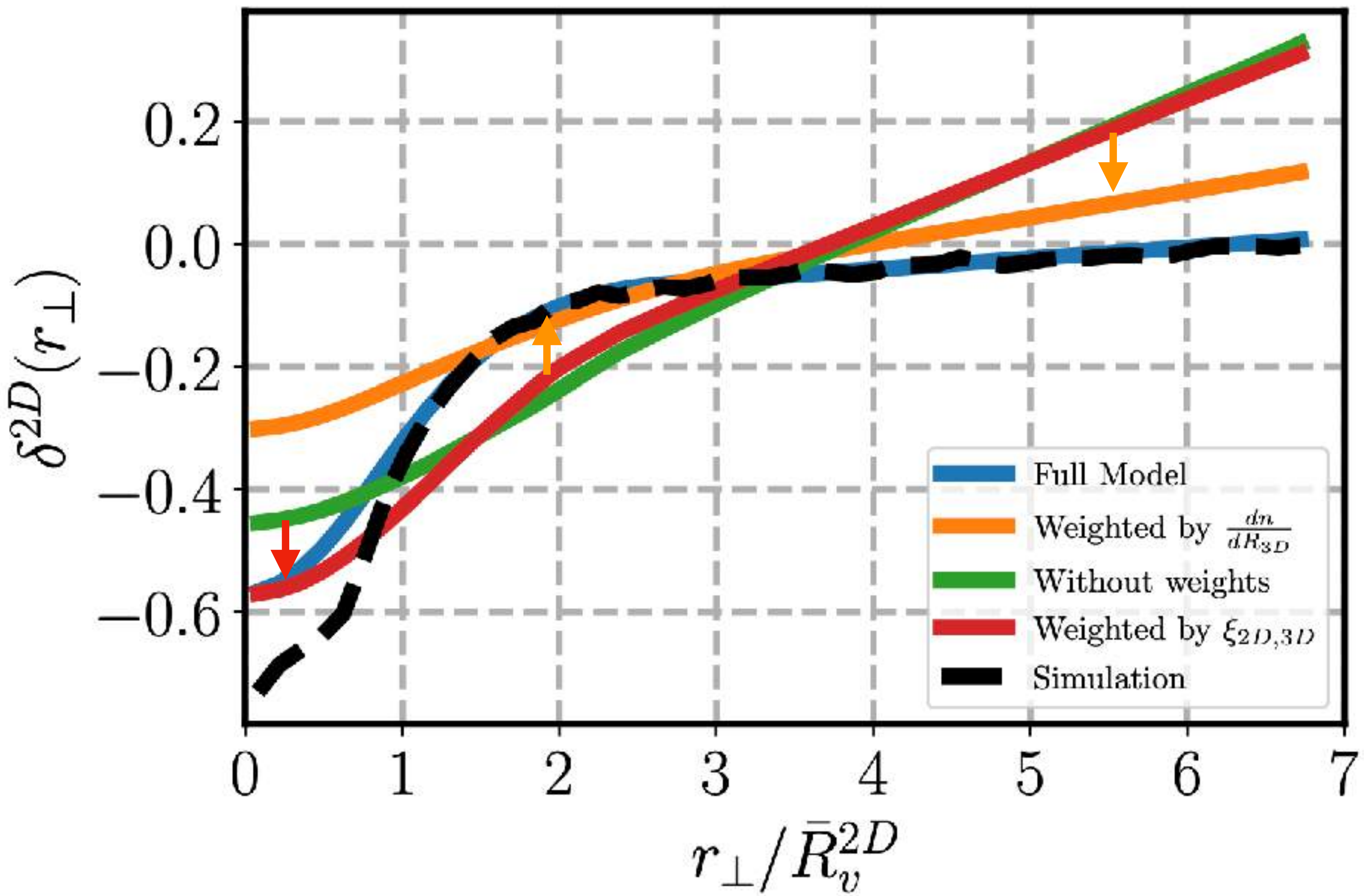


# Preliminary Result ($8 < R_v^{2D} < 15$)

$$\Sigma(r_\perp | R_{2D}, \Delta_{2D}, \Delta_{3D}) = \frac{1}{N} \int dR_{3D} \frac{dn_v}{dR_{3D}}(R_{3D} | \Delta_{3D}) \times \int dx_\perp d\phi \, P(x_\perp | R_{3D}, R_{2D}, \Delta_{3D}, \Delta_{2D}) \times \int dr_\| \delta_{3D}(|\boldsymbol{r}_\perp - \boldsymbol{x}_\perp| | R_{3D}, \Delta_{3D})$$

$$\simeq$$

$$\Sigma(r_\perp | R_{2D}) = \int d\ln R_{3D} \frac{dn_v}{d\ln R_{3D}} \int dx_\perp d\phi \xi_{2D,3D}(x_\perp) \int dr_\| \, \delta_{3D}(|\boldsymbol{r}_\perp - \boldsymbol{x}_\perp| | R_{3D})$$



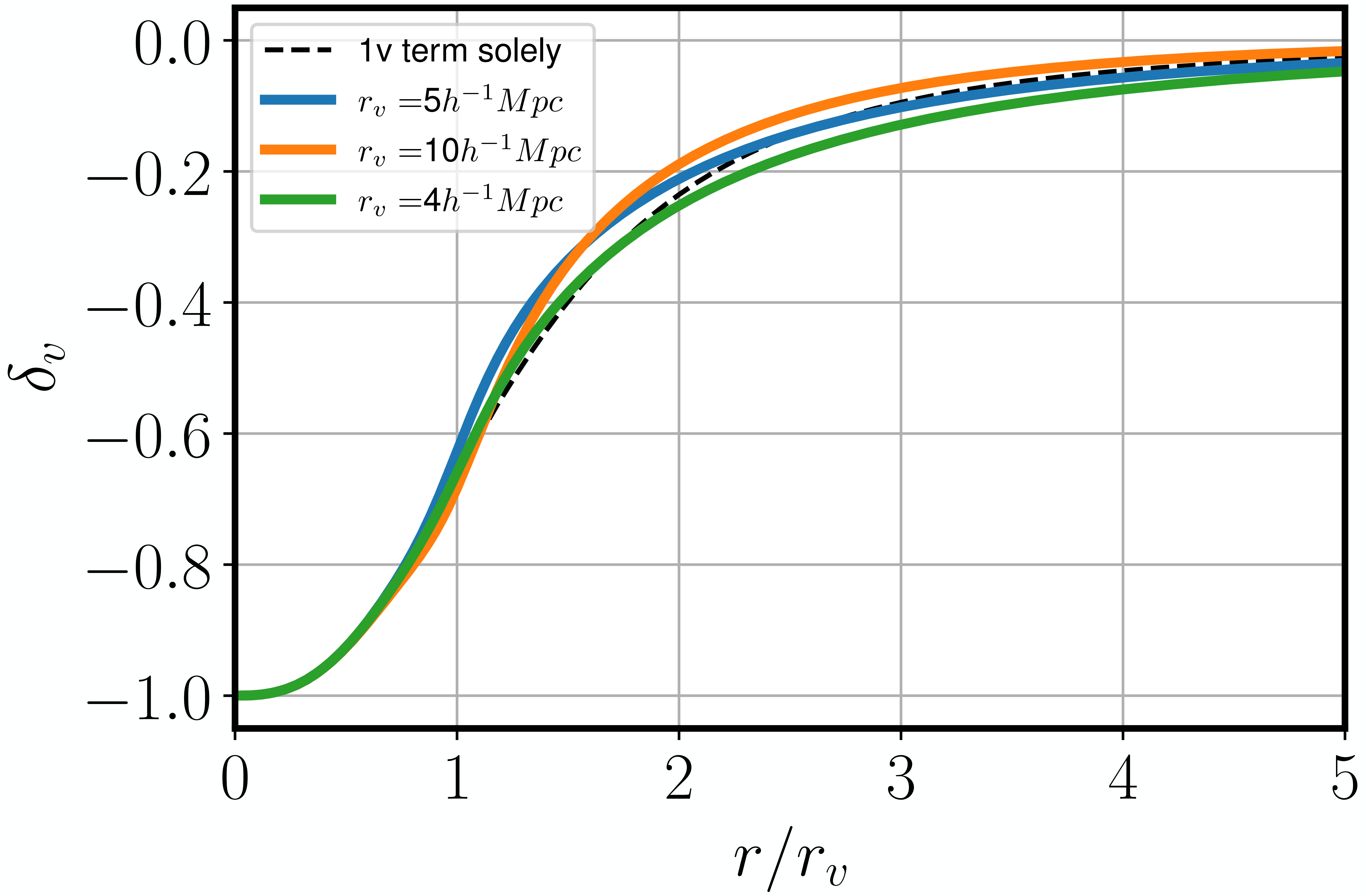
# Information in the Void Profile

Starting from the 3D void profile (Voivodic et al., 2020):

$$\frac{\rho_v^{3D}(r_z, r_p \,|\, r_v)}{\bar{\rho}_m^{3D}} \equiv \xi^{1V} + b_v \xi_g$$

Where,

$$\xi^{1V} = \frac{1}{2}\left[1 + \tanh\left(\frac{\ln\left(\sqrt{\left(r_\mathrm{p}/r_v\right)^2 + \left(r_z - D_A(z)/r_v\right)^2}\right) - \ln\left(r_0\right)}{s}\right)\right]$$



# Conclusions and Future Perspectives

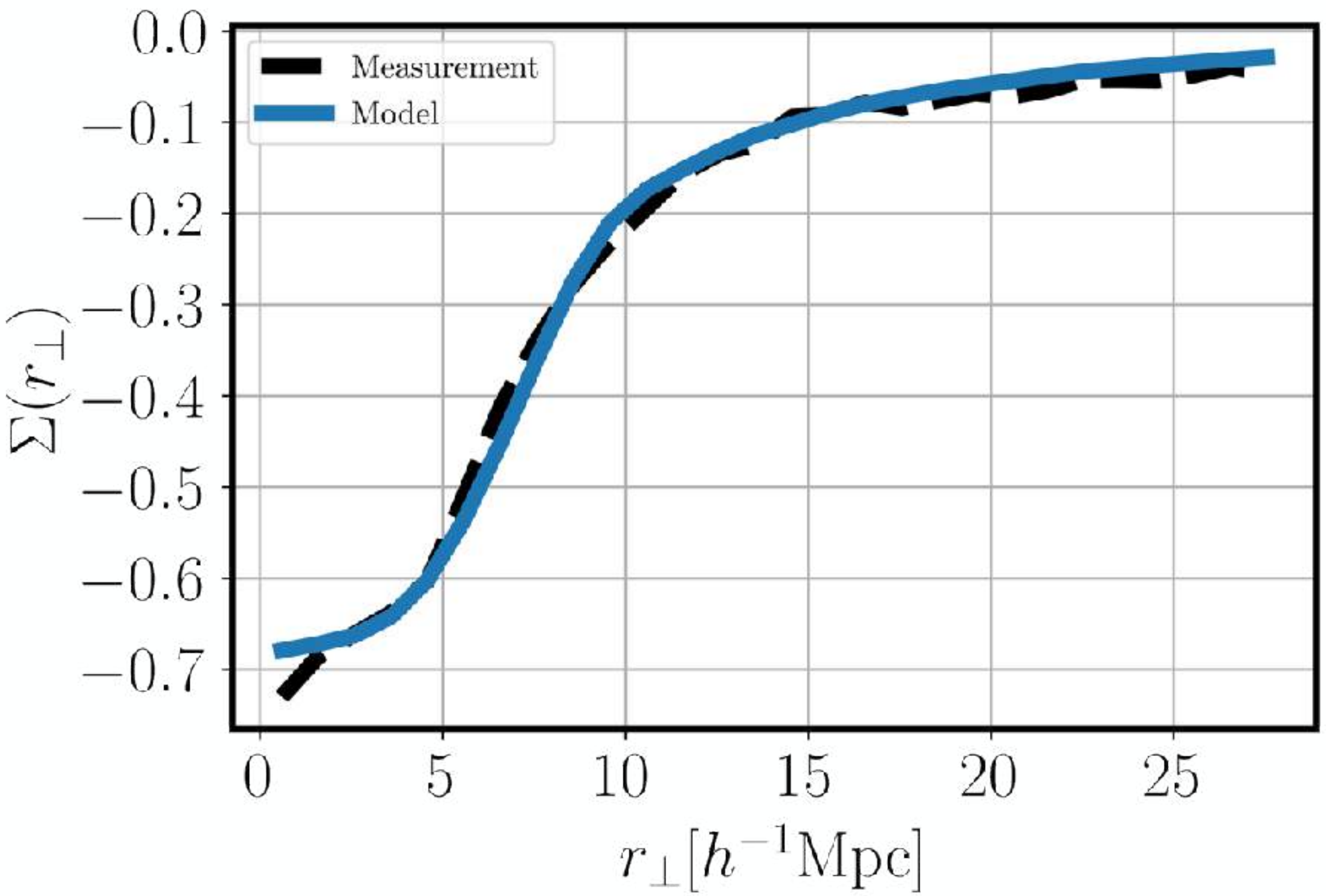
- Void-Lensing can be measured with a significant S/N by future spectroscopic surveys.
- Void-Lensing can be a key test of gravity on large scales since voids are the ideal environment and lensing is directly sensitive to the total matter field.
- The VL modelling shows that the measured signal depends on the VIA
- Cosmological constraints with VL is yet to be obtained. We've paved the avenue for it by: (i) showing the condition necessary to measure proj. Void profiles and (ii) proposing a simple connection between what we measure and 3D voids.

Thank you for your attention!

# 2D-3D Connection

$$\delta_v^{2D}(R_v^{2D}) = F[\delta_v(R_v^{3D}), R_v^{2D}] = \int dR_v^{3D} P_R(R_v^{3D}) \int d\xi P_\xi(\xi \,|\, R_v^{3D}) \int dr_{//} \delta_v^{3D} \left( \sqrt{\alpha r_{//}^2 + (r_\perp - \xi)^2} \,|\, R_v^{3D} \right)$$

$$\approx \frac{1}{L} \sum_i \omega_i \int_0^L dr_{//} \delta_v^{3D} \left( \sqrt{(\alpha_i r_{//} - L/2)^2 + r_\perp^2} \,|\, R_{v,i}^{3D} \right)$$




$R_v^{2D} \in [5,8](h^{-1}\mathbf{Mpc})$

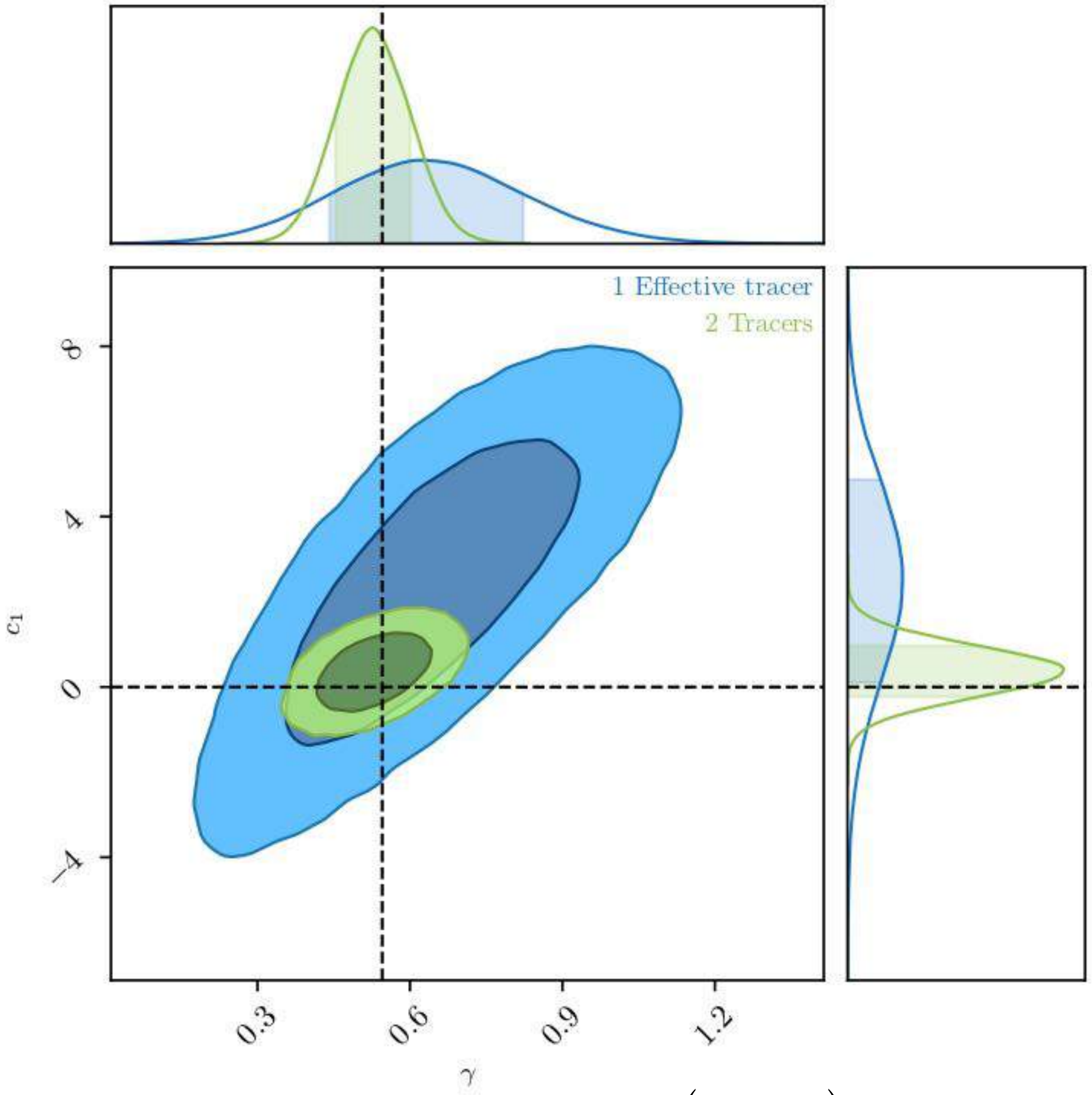
$R_{v,1}^{3D} \in [5,8](h^{-1}\mathbf{Mpc})$

$R_{v,2}^{3D} \in [8,15](h^{-1}\mathbf{Mpc})$

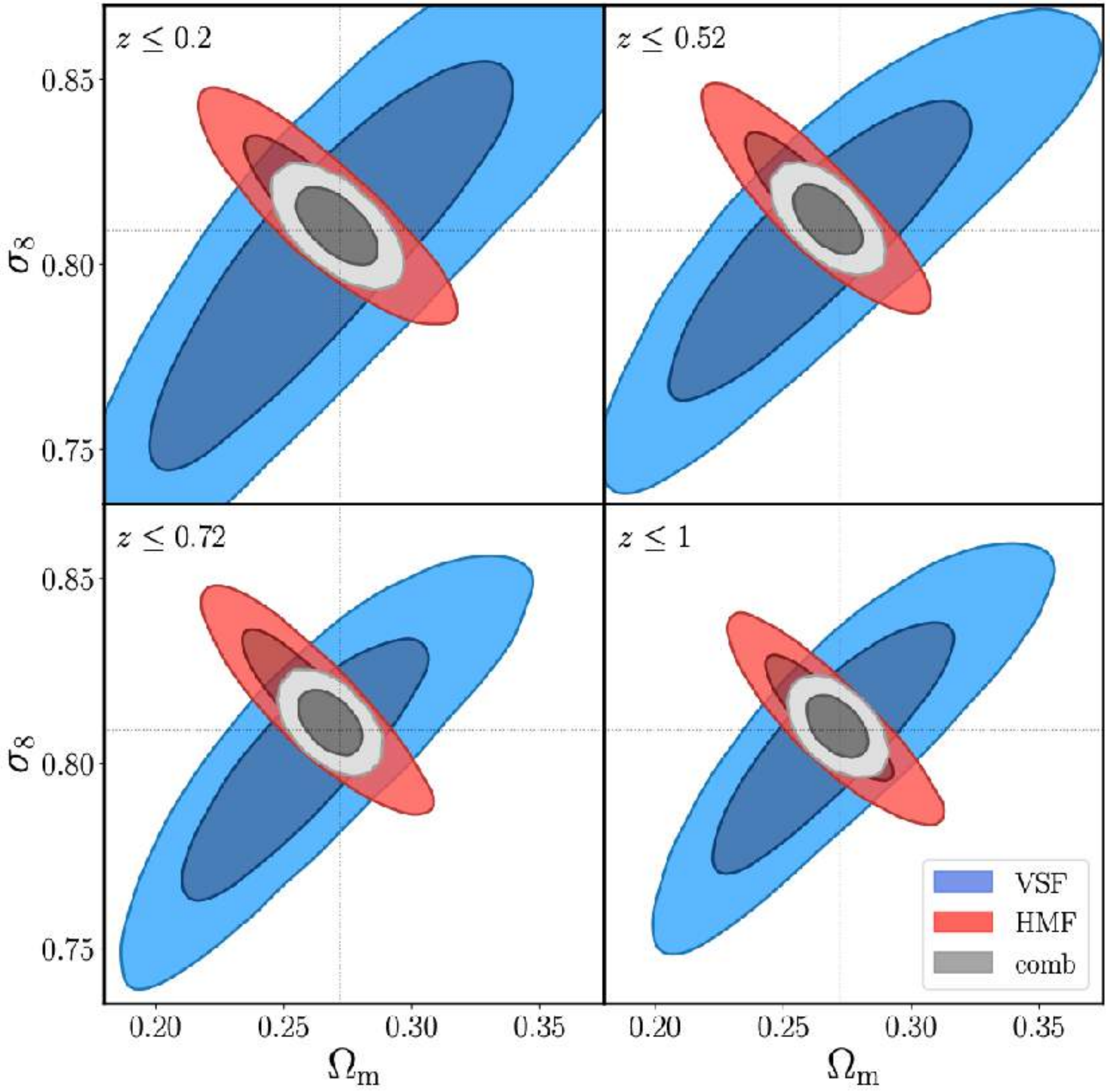
$\omega_1 = 1.11,\ \omega_2 = 0.36,$

$\alpha_1 = 0.59,\ \alpha_2 = 0.78$

# Why Voids? – Voids As Just Another Tracers of LSS




$$f(k, z, \gamma) = \Omega_m^{\gamma}(z) + c_1\left(k - k_0\right)$$




D. Pelliciari et al. (2023)

# Lovelock's Theorem

"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."

$$S^{D}_{\text{grav}} = \frac{M^2_{Pl,D}}{2}\int d^D x\sqrt{-g_D}R_D$$

# Lovelock's Theorem

"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."

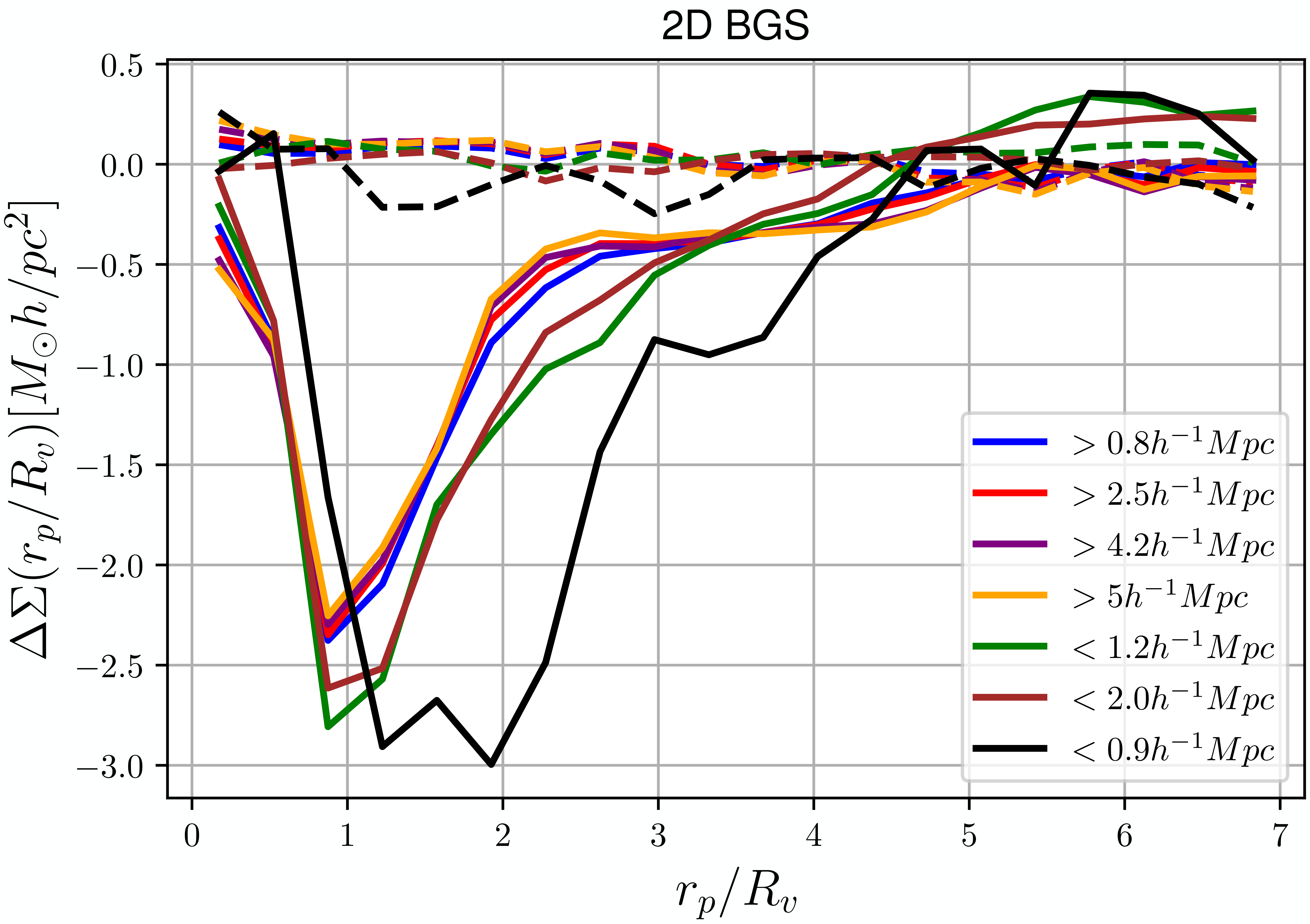
$$S_{\text{grav}} = \frac{M_{Pl}^2}{2} \int \sqrt{-g}\, d^4x \left[ R + \beta_1 R \nabla_\mu \nabla^\mu R \right] .$$

# Lovelock's Theorem

"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."

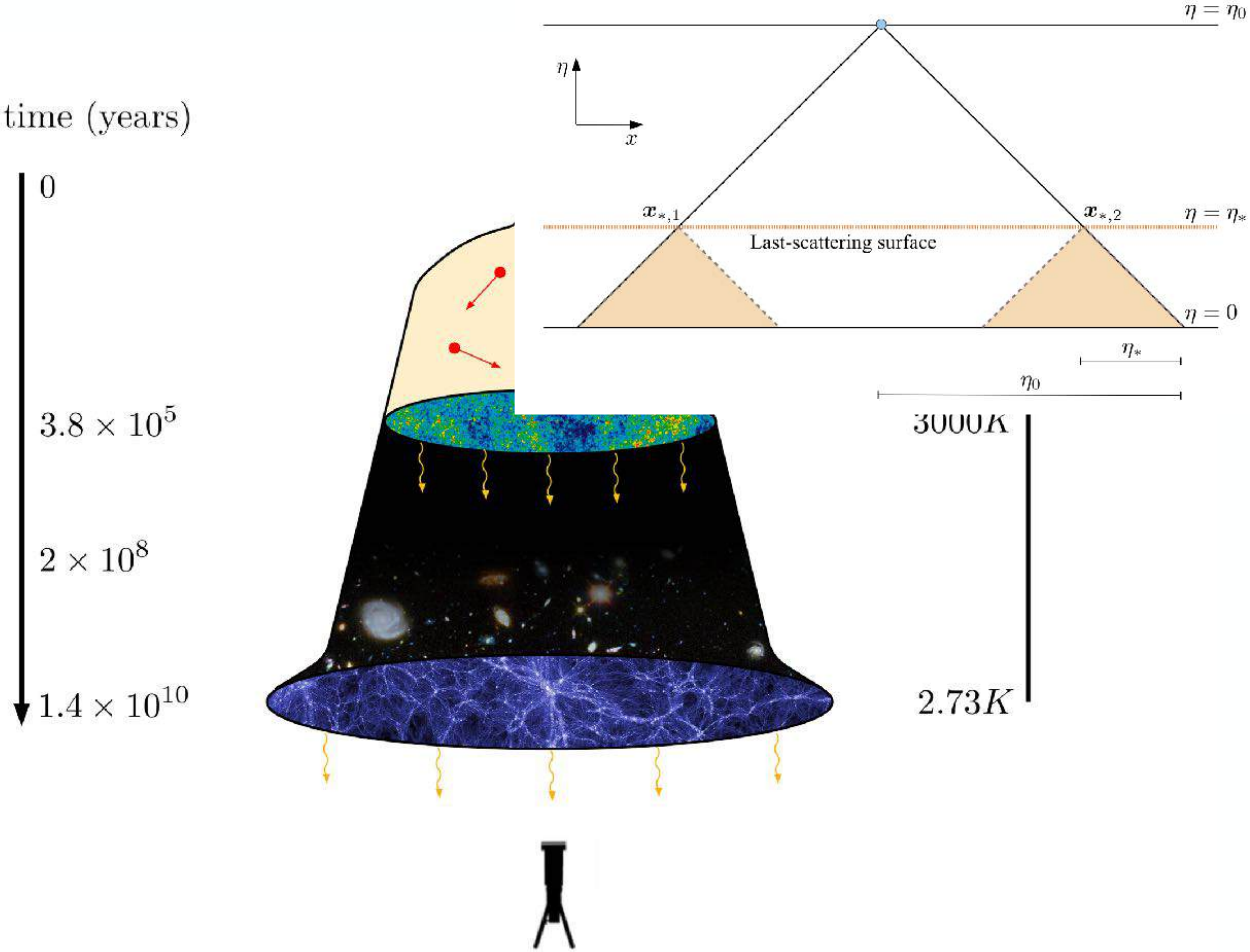
$$S_{\text{grav}} = \frac{M_{Pl}^2}{2}\int\sqrt{-g}\,d^4x\left[R + f\left(\frac{1}{\Box}R\right)\right]$$

# The Role of Void Radius

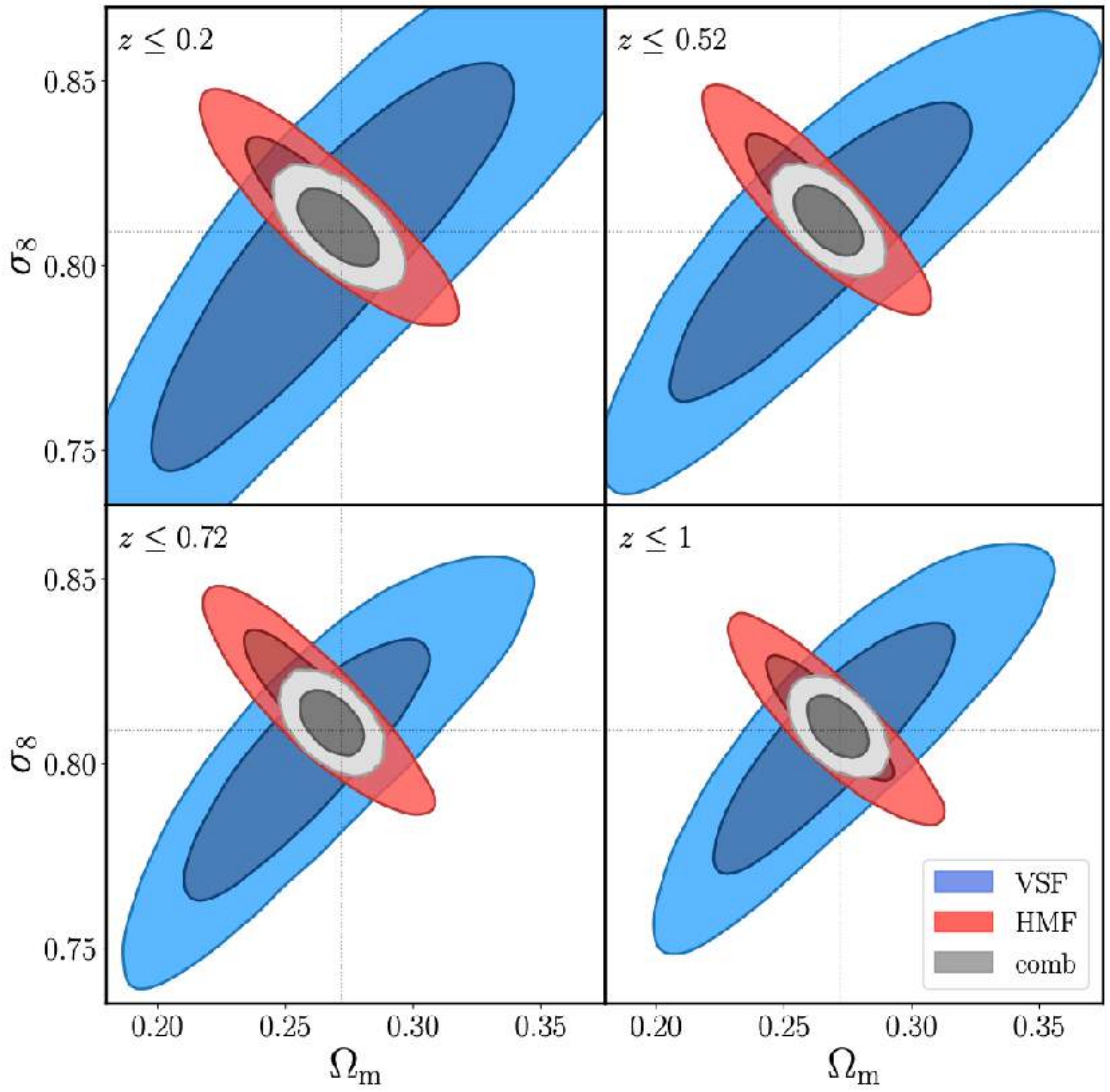


# What Is Observational Cosmology?

Dodelson and Schimdt



# Voids As Just Another Tracers of LSS

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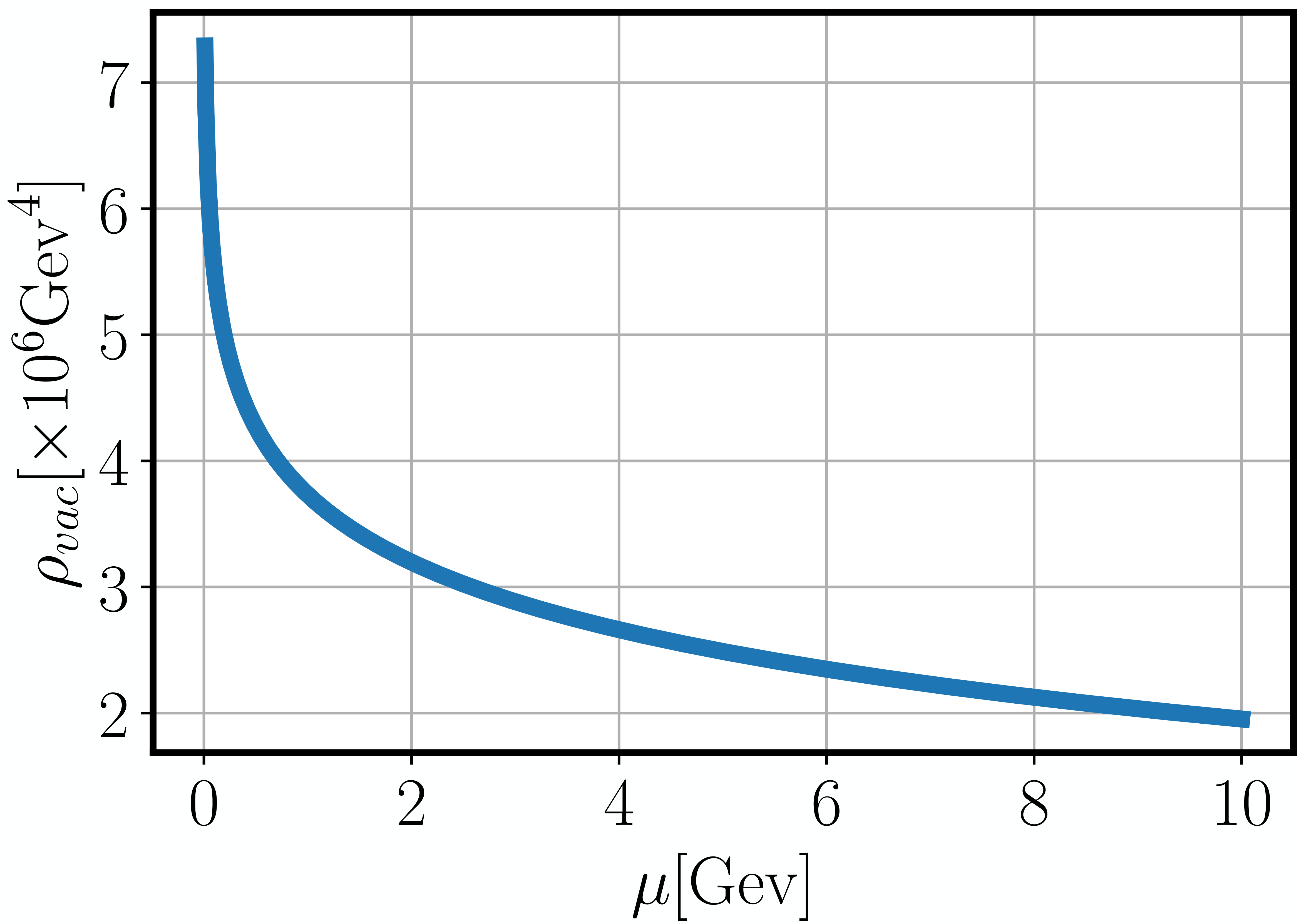
# The Biggest Puzzle in Cosmology: the Cosmological Constant

By using dimensional regularization:

$$\rho_{vac} = \sum_i n_i \frac{m_i^4}{64\pi} \ln\left(\frac{m_i^2}{\mu^2}\right)$$

Only the Higgs contribution gives $\sim 10^{44} eV$



# Why Voids? – The Information in Void Counts (S. White, 1978)

$P(X_i) \equiv$ The probability that there is a galaxy in $dV_i$ at $x_i$

$P(\bar{X}_i) \equiv$ The probability that there is no galaxy in $dV_i$ at $x_i$

$P(\Phi_0(V)) \equiv$ The probability that there is no galaxy at V

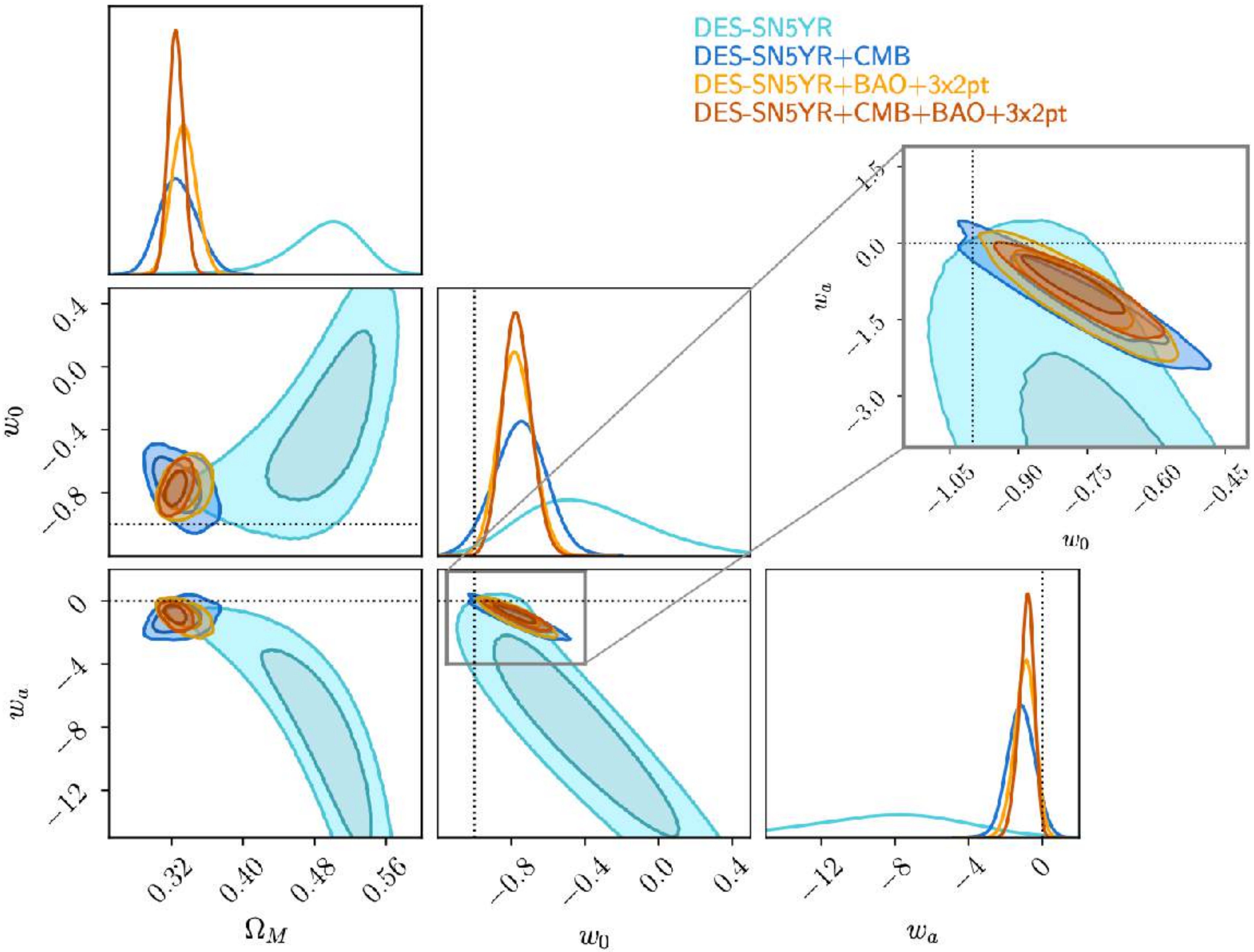
$$P(\Phi_0(V)) = P(\bar{X}_1, \ldots, \bar{X}_N) = 1 - \left[ \sum_{i=1,N} P(X_i) - \sum_{j<i} P(X_i X_j) + \sum_{k<j<i} P(X_i X_j X_k) - \ldots \right]$$

But

$$P(X_1, \ldots, X_N) = n^N \left[ 1 + \sum \xi^{(2)}(x_i, x_j) + \sum \xi^{(3)}(x_i, x_j, x_k) + \ldots + \xi^{(N)}(x_1, \ldots, x_N) \right] dV_1 \ldots dV_N$$

The probability of finding a "hole" of a certain size contains the whole hierarchy of N-point functions!

# Hints for Deviations From a Cosmological Constant!




T. M. C. Abbott et al. (2024)