Constraints on long-range neutrino self-interactions from large-scale structure

Xuheng Luo

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DPF-Pheno 2024

Based on upcoming work with David E Kaplan and Surjeet Rajendran

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Equivalence principal test of neutrinos

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Motivation

- Long range force between neutrinos are weakly constrained

$$\mathcal{L} \supset \frac{1}{2} m_\phi^2 \phi^2 + m_\nu \bar{\nu}\nu + g\phi\bar{\nu}\nu$$

  - Neutrino scalar field interaction $g_{\nu\phi} \lesssim 7.7 \times 10^{-7}$ or $10^{47} \times$ Gravity [Berryman:2022]
- Hard collisions are inefficient probe $\Gamma \propto g_{\nu\phi}^4$

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- Hard collisions are inefficient probe $\Gamma \propto g_{\nu\phi}^4$
- Usually long-range interaction detection benefit from coherent enhancement
- But it is difficult to have large coherent enhancement for neutrinos in lab,
- Our work: looking for long-range interaction in the cosmic neutrino background ($n_\nu \sim 10^{75}/Mpc^3$)

Model Setup

$$\mathcal{L} \supset \frac{1}{2}m_\phi^2\phi^2 + m_\nu\bar{\nu}\nu + g\phi\bar{\nu}\nu$$

- We turn on long range force between neutrinos that is stronger than gravity
- $$G' = \frac{g^2}{4\pi m_\nu^2} \gg G$$
- In the linear regime, the system can be solved perturbatively [EoM: Esteban:2021]
  - Background and linear perturbation evolution (analytical ✓ CLASS ✓)
- Significant enhancement of neutrino perturbation ($\delta_\nu \gtrsim 1$)

Growth of Perturbation

- $\ddot{\delta}_\nu + 2H\dot{\delta}_\nu = \frac{3}{2}H^2\left[\left(1 + \frac{G'}{G}\frac{k^2}{k^2+a^2m_\phi^2}\right)\Omega_\nu\delta_\nu - \frac{k^2}{k_{fs}^2}\delta_\nu + \Omega_{cdm}\delta_{cdm}\right]$

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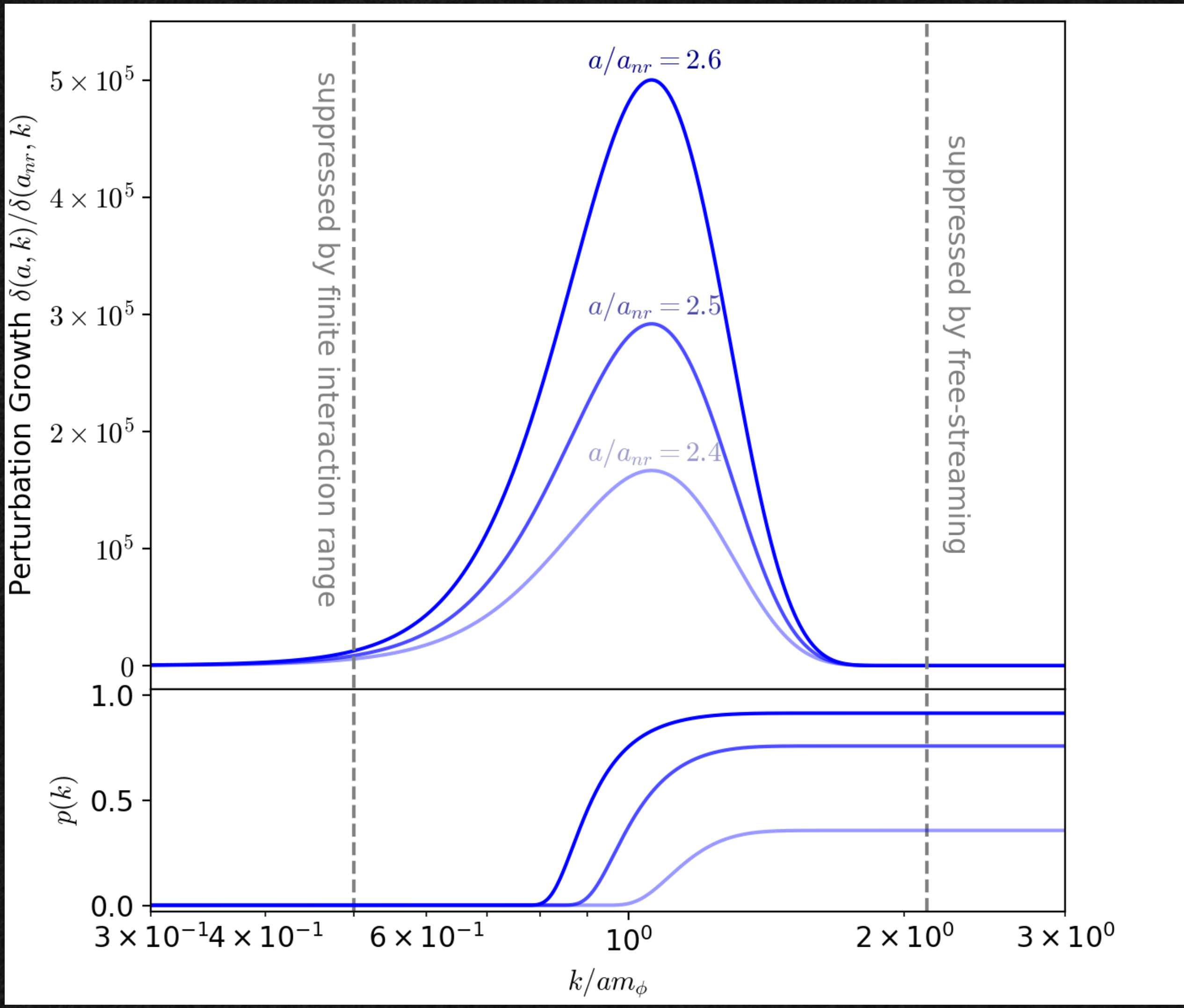
- Very fast growth mode at $\frac{k}{a} \gtrsim \mathrm{m}_\phi$
- Scale dependent growth: suppressed at $\frac{k}{a} \lesssim \mathrm{m}_\phi$

  also suppressed at $k \to \infty$



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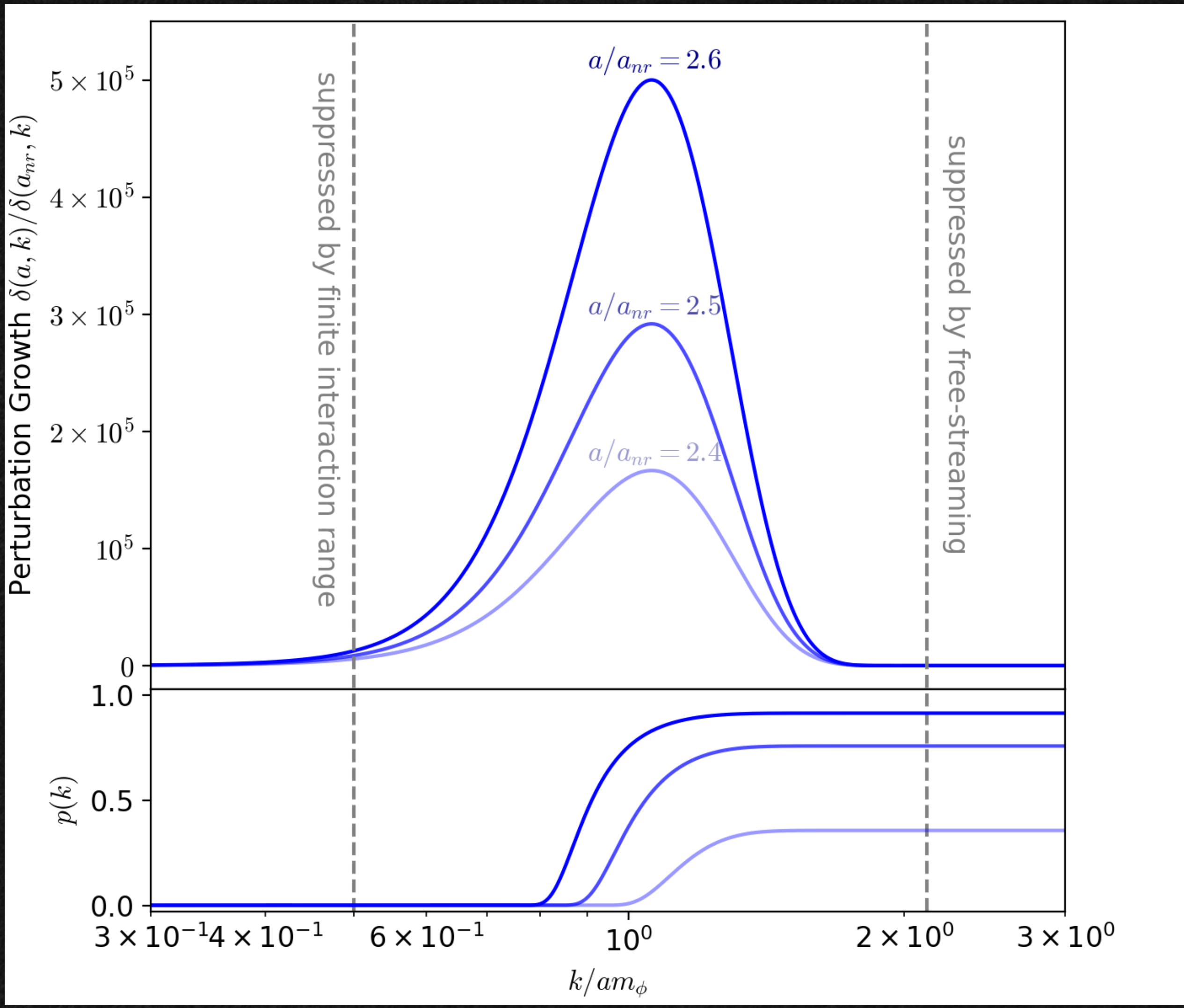
- Peaked structure formation at $\frac{k}{a} \sim m_\phi$ based on Press–Schechter formalism [Domenech:2023]
- We assume $r_{\nu halo} \approx m_\phi^{-1}$, $M_{\nu halo} \approx 4\pi\rho_\nu/3m_\phi^3$ forms when $\delta_\nu(k = am_\phi) \approx 1$



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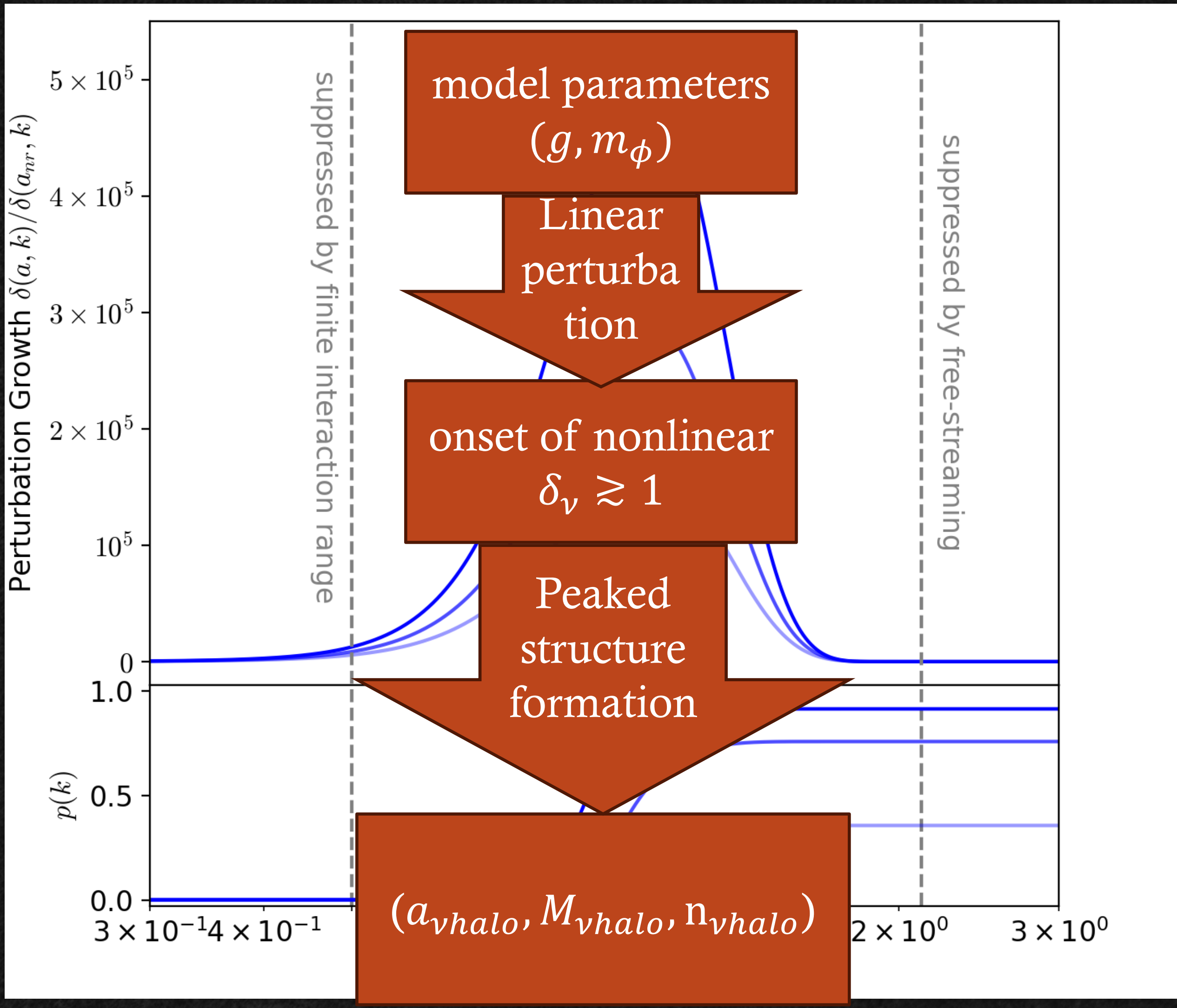
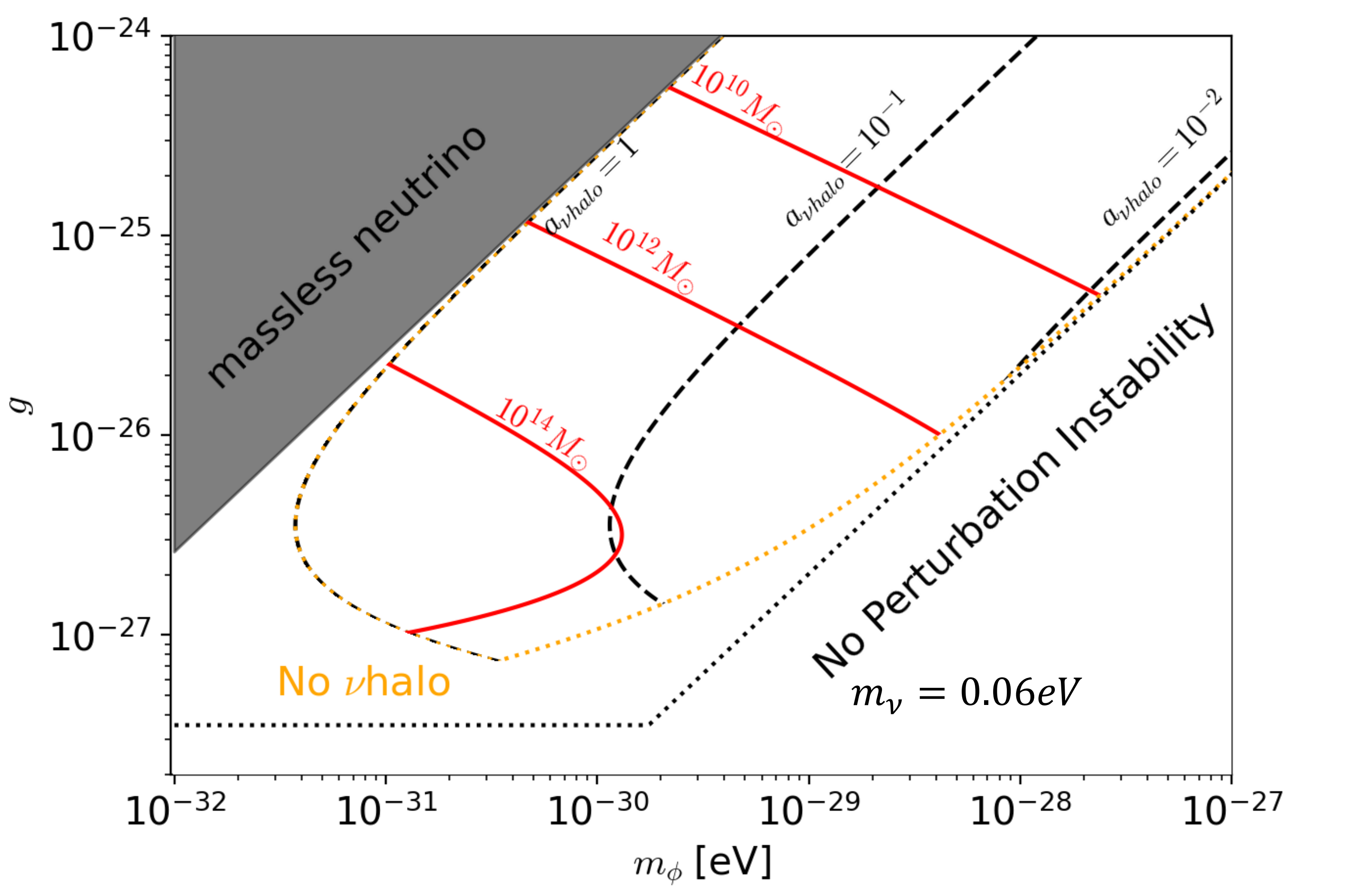


Formation of νhalos

- Very massive halo formation from neutrinos
- Formation redshift and mass non-trivially depend on (g, m_ϕ)
- $M_{\nu\text{halo}}: \lesssim 10^{14} M_\odot$
- $a_{\nu\text{halo}}: 1 \sim 0.01$
- Neutrinos are 0.5% of matter, how to observe these structure?



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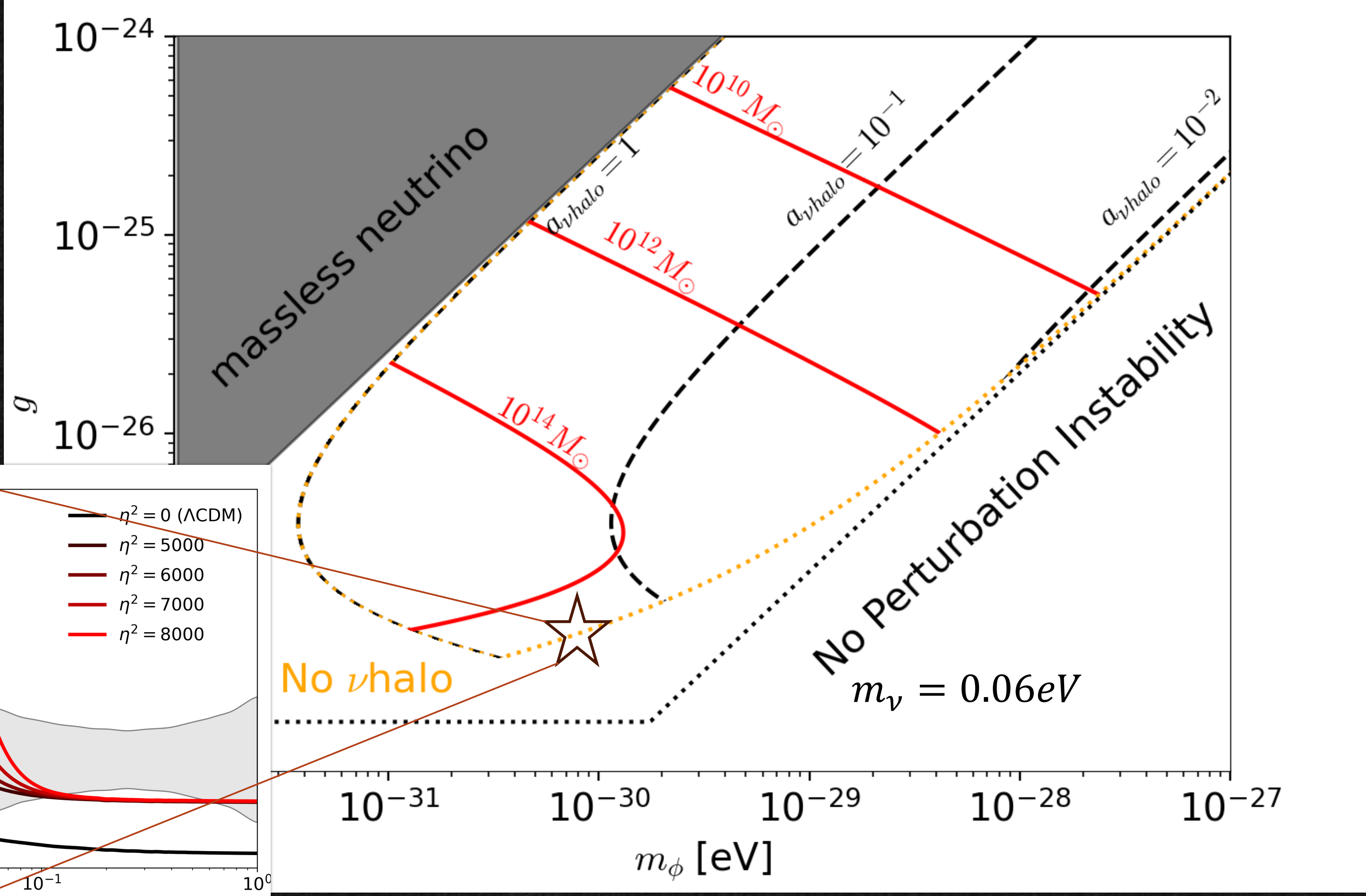

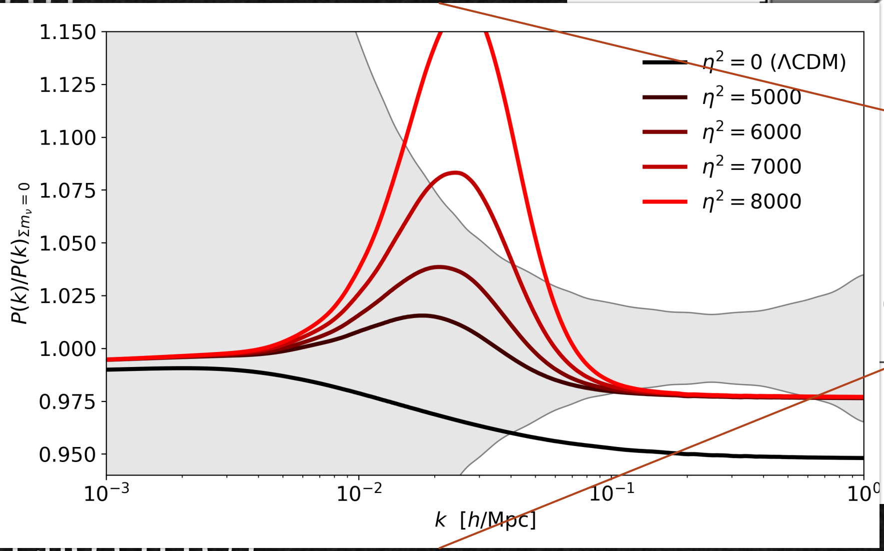

Impact on matter power spectrum

- Matter perturbation from neutrinos can be large even though $\Omega_\nu \approx 0.5\%$
- $\delta_\nu \sim 1$, at $z \sim 100$ $\rho_\nu \delta_\nu \sim \rho_{cdm} \delta_{cdm}$
- Massive primordial black hole can enhance structure formation even with small abundance [Carr:2018, Inman:2019, Liu:2022]

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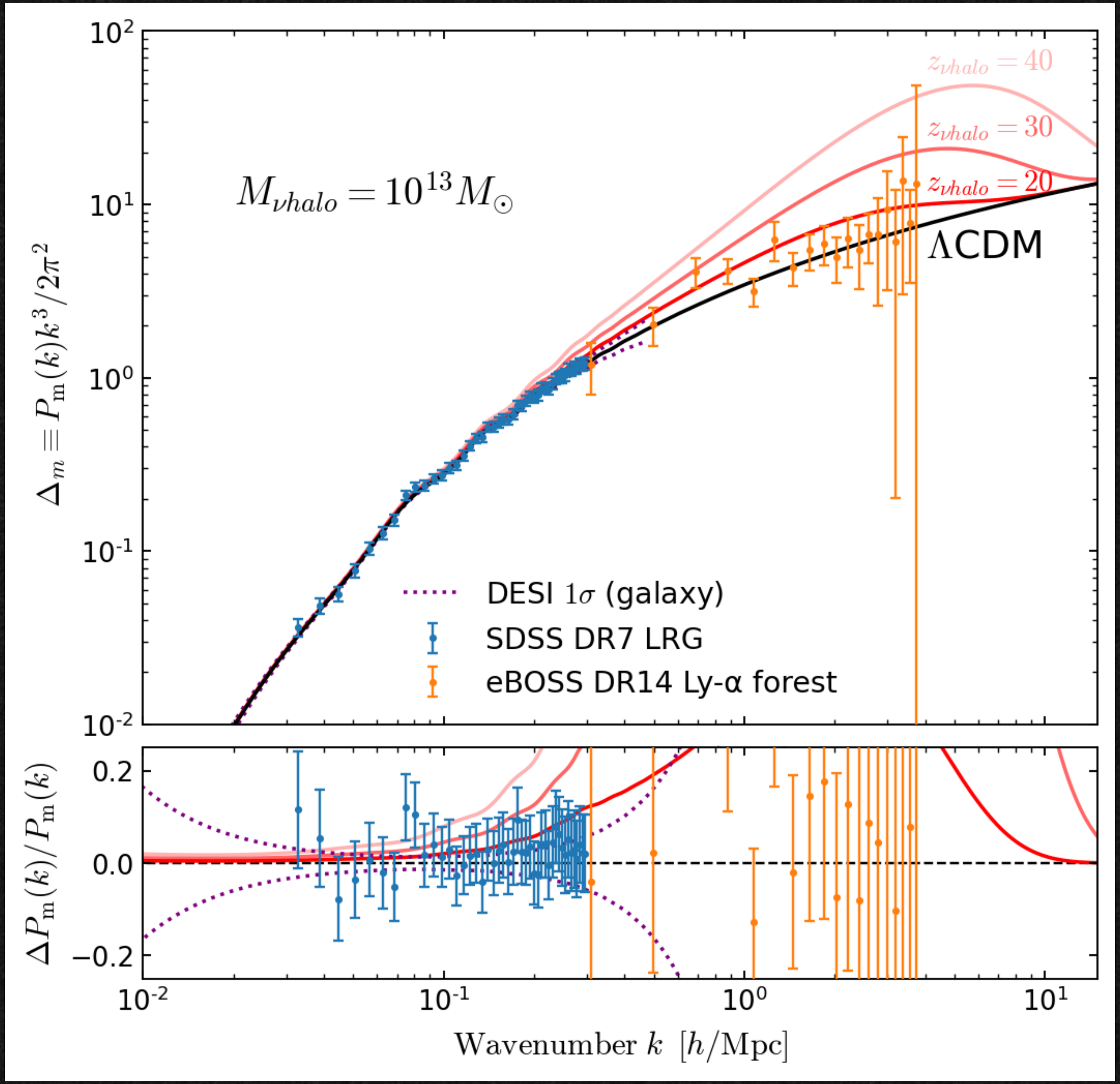
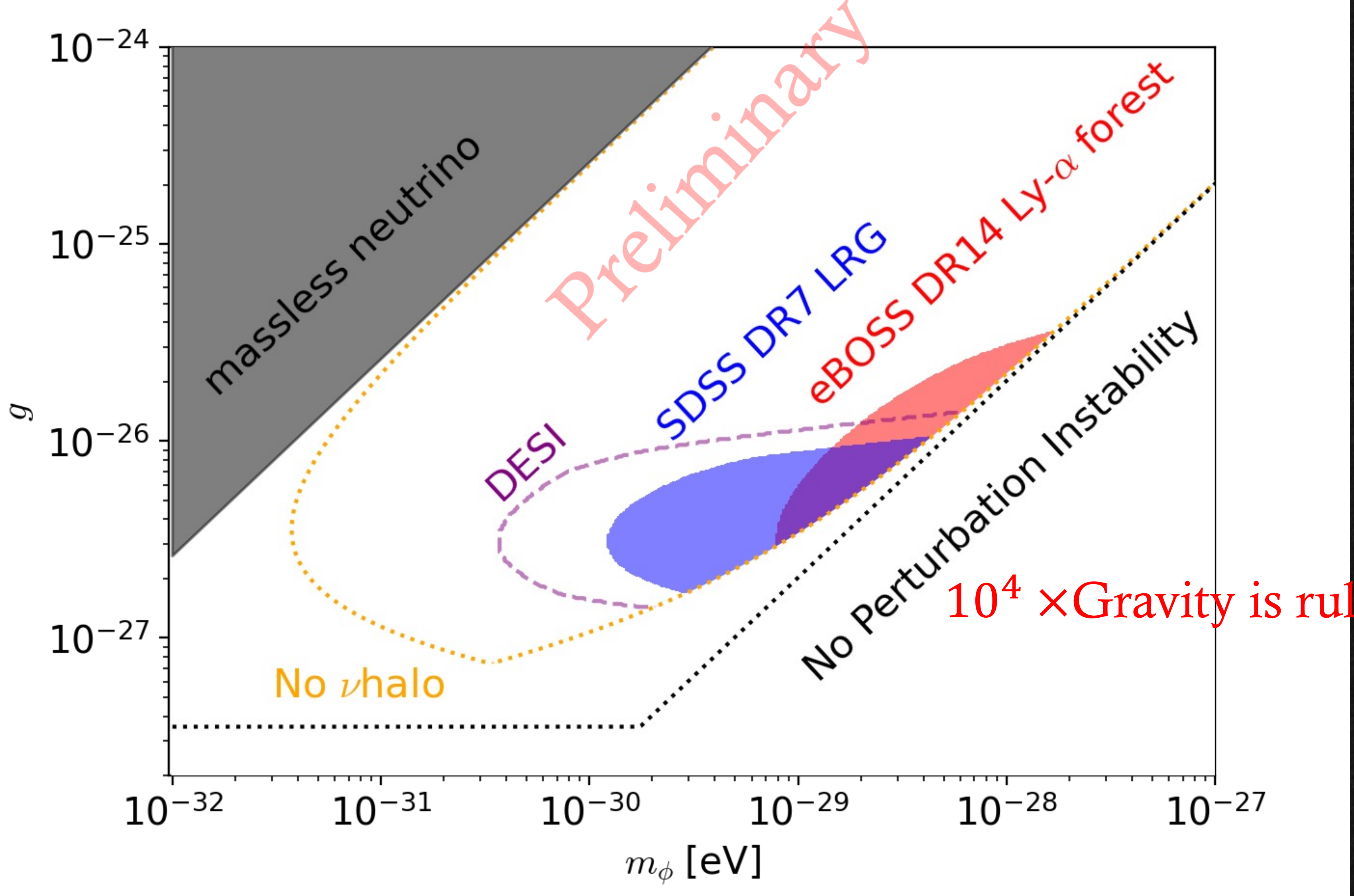
- *vhalos* are effectively a point mass at observation scales, we model their mps by
- $$P_m(a) = D_+(a, a_{vhalo})^2 (1 - \Omega_\nu)^2 P_{cc}(a_{vhalo}) + D_+(a, a_{vhalo})^2 \Omega_\nu^2 P_{vv}(a_{vhalo})$$
- $$P_{vv} = 1/\bar{n}_{vhalo}$$
- corrections need to be added at small scales

Results



$z_{\nu halo} = 40$
$z_{\nu halo} = 30$
$z_{\nu halo} = 20$
ΛCDM
$M_{\nu halo} = 10^{13} M_\odot$
DESI 1σ (galaxy)
SDSS DR7 LRG
eBOSS DR14 Ly-α forest
$\Delta_m \equiv P_m(k) k^3/2\pi^2$
$\Delta P_m(k)/P_m(k)$
Wavenumber k $[h/\mathrm{Mpc}]$

Results



10^4 ×Gravity is ruled out!

Summary

- Non-linear structure of neutrinos can form when long-range interaction is strong
- Potential large impart on structure formation from neutrinos non-linear structure
- LSS is not the only way to look for it, but also from CMB, galaxy…

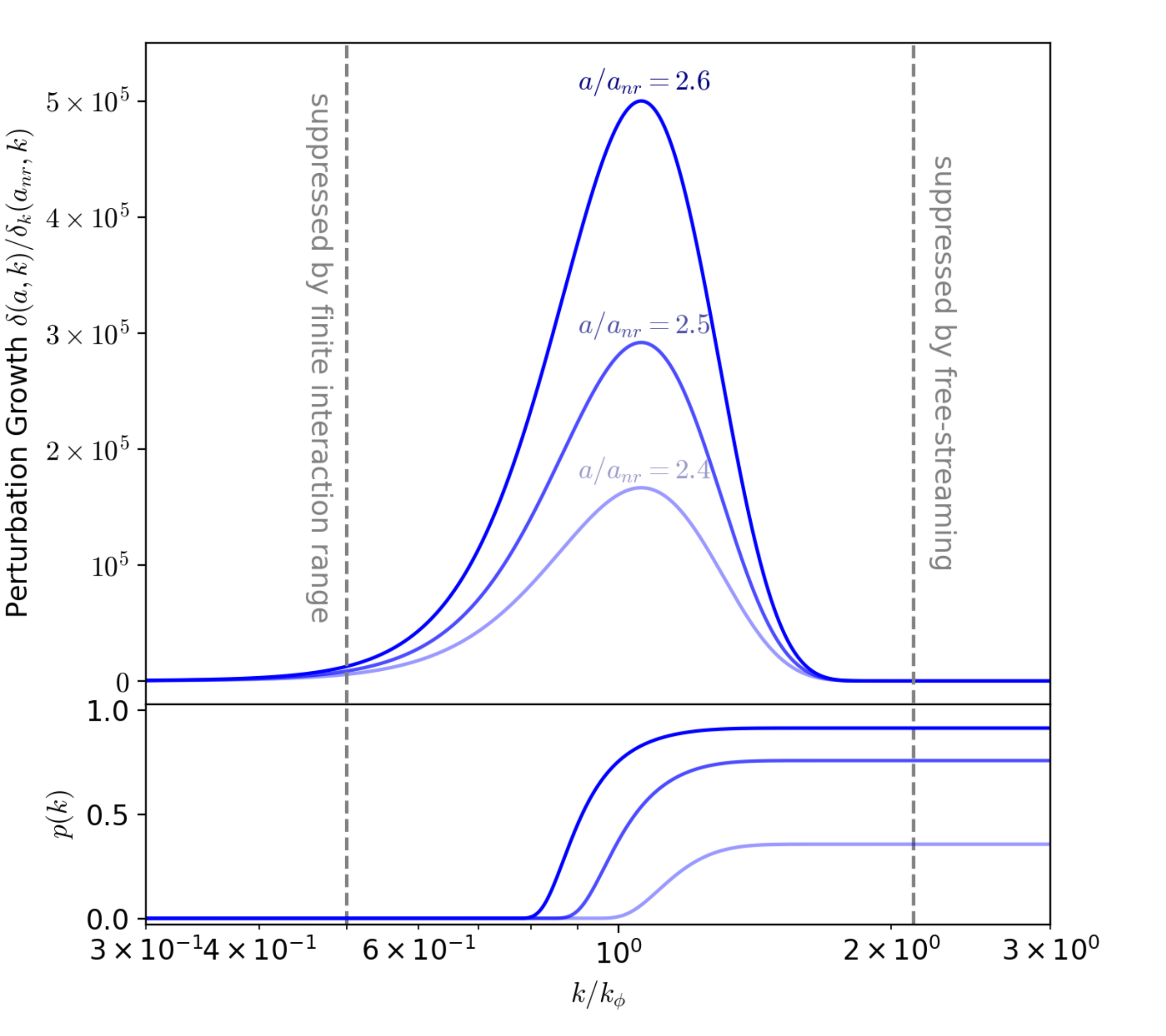
Thanks!

Formation of νhalos

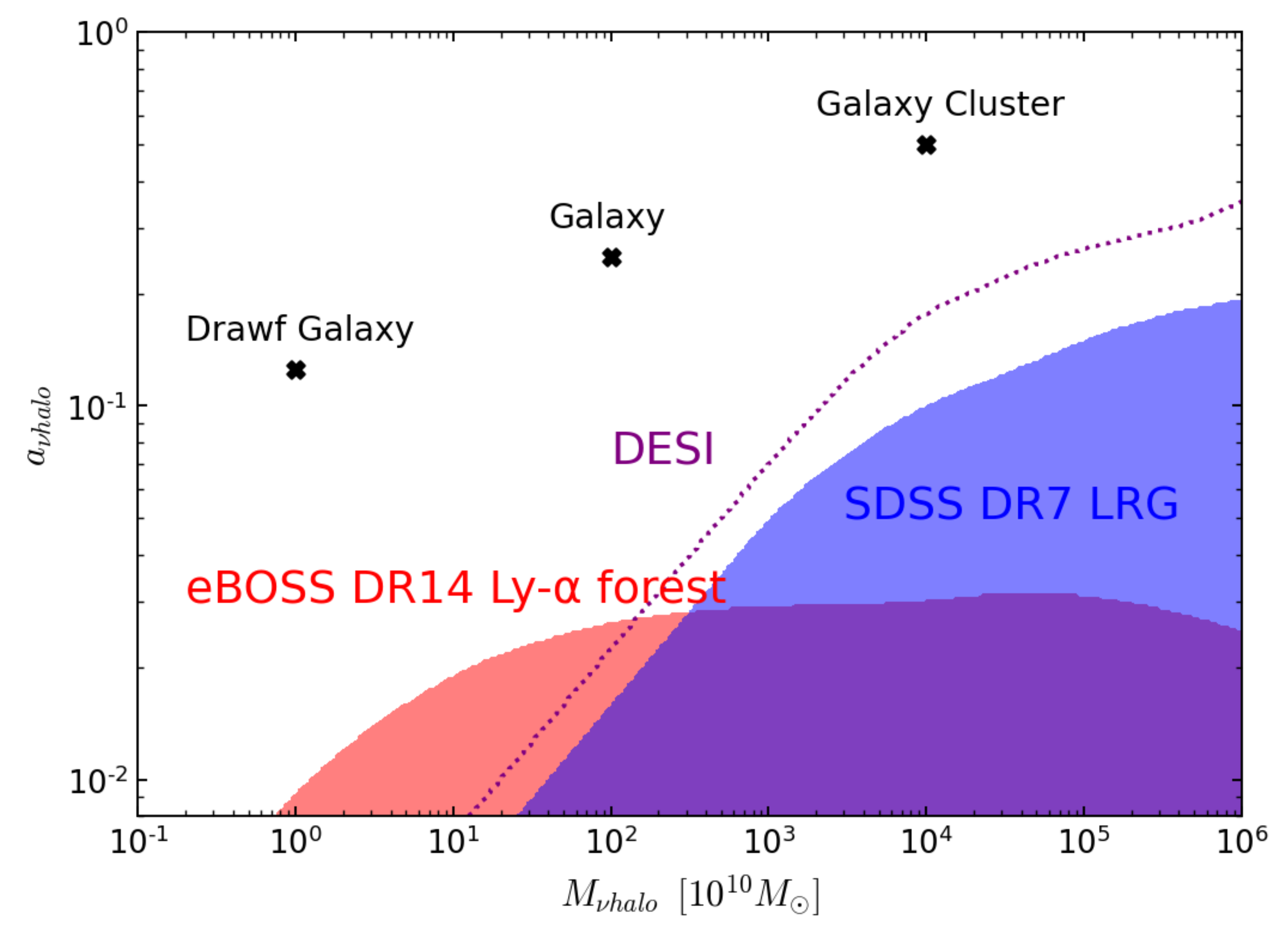
- Press-Schechter formalism
  - Perturbations are Gaussian random field
  - νhalo form when perturbation exceed 1
  - Predict halo formation probability

$$p(R_L, z) = 2 \times \frac{1}{\sqrt{2\pi}} \int_{\delta_{cr}/\sigma(R_L,z)}^{\infty} dx e^{-x^2/2}$$

$$\sigma(R_L, z) = \int \frac{d^3k}{(2\pi)^3} P_{\nu\nu}(k, z) |W_{R_L}(k)|^2$$



Results

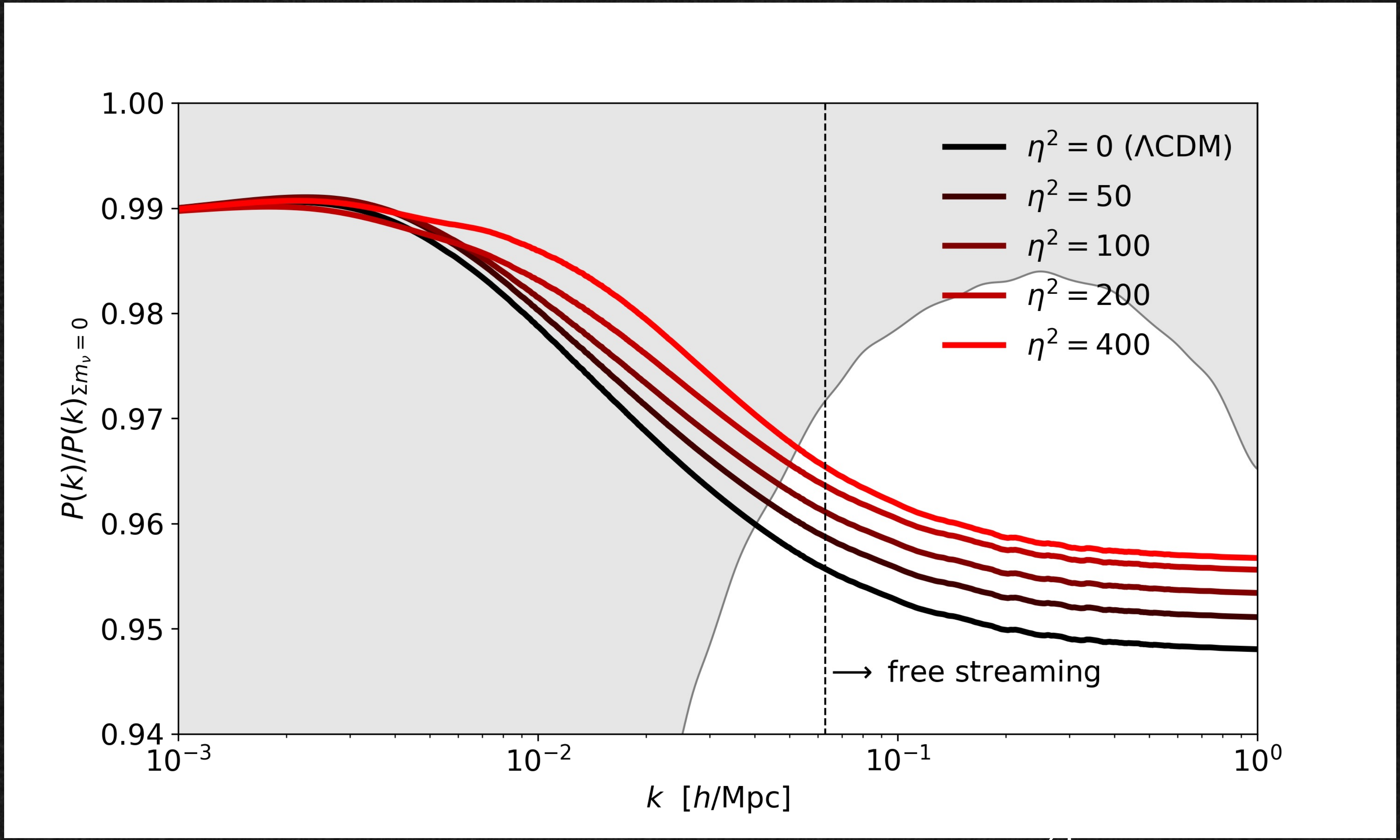


Galaxy Cluster
Galaxy
Drawf Galaxy
DESI
SDSS DR7 LRG
eBOSS DR14 Ly-α forest
$a_{\nu halo}$
$M_{\nu halo}\ [10^{10} M_\odot]$

νhalo model

- Seed effect: dense object can grow from accreting nearby dm → minihalos
- νhalo is surrounded by secondary infall of dm when $\delta_m \sim 1$
- Growth of minihalos $M_{mh} \propto a$
- Profile can be analytically derived (Bertschinger, E 1985, Fillmore&Goldreich 1984)
- $\rho_{mh} = 2\rho_c \left(\frac{r}{r_{mh}}\right)^{-\frac{9}{4}}$
- Need to cut off the profile at $r \sim r_{\nu halo}$
- Matter power spectrum $P_{mh}^{1h} = \frac{1}{n_{mh}} |y(k,a)|^2$
- $y(k,a) = \frac{\int_0^{r_{mh}} 4\pi r^2 dr \rho(r,a) \frac{\sin\left(\frac{kr}{a}\right)}{\frac{kr}{a}}}{M_{mh}}$

Background: mass variation



Perturbation: enhanced δ_ν growth