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

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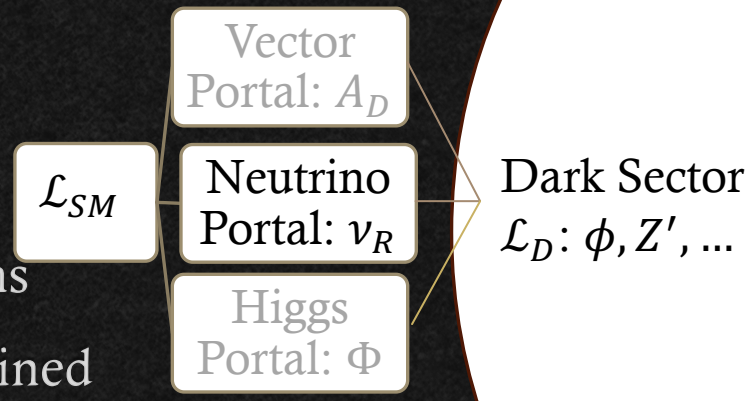
Fundamental Physics from Future Spectroscopic Surveys

Motivation



- Light particle in the neutrino sector can raise long range interactions
- However … long range force between neutrinos are weakly constrained
  - Neutrino scalar field interaction $g_{\nu\phi} \lesssim 7.7 \times 10^{-7}$ or $10^{47}\times$ Gravity [Berryman:2022]

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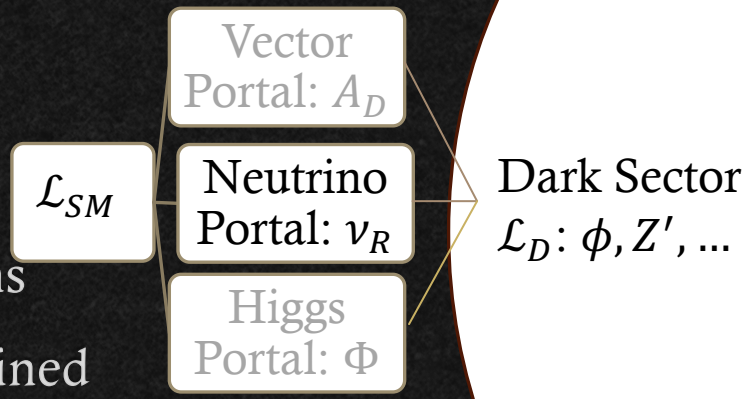

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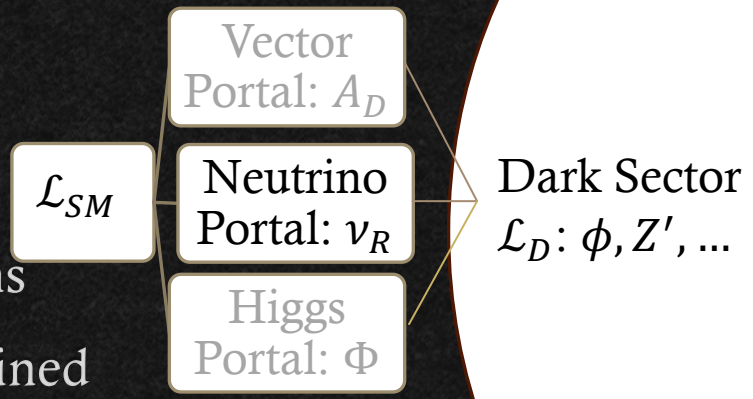

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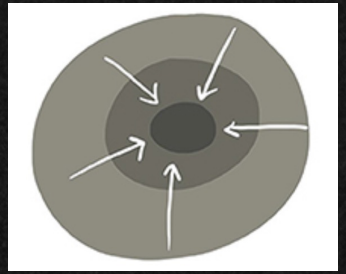
- Reason: long range interaction detection benefit from coherent enhancement ($N \sim N_A \sim 10^{24}$)
- Difficult to have large coherent enhancement for neutrinos in lab, hard collisions ($N_\nu \sim 1$)
- Solution: looking for coherent interaction in the cosmic neutrino background ($n_\nu \sim 10^{75}/Mpc^3$)

Toy example: CνB in the Milky Way



- Typical velocity of CνB today (minimal mass): $v_\nu \sim 10^{-2}$
- Jeans criterion: collapse happen if pressure induced gravity took over thermal pressure
- $$\text{if } \mathrm{P_G} \sim \frac{GM_\nu^2}{R^4} \gtrsim P_{th} \sim \rho_\nu v_\nu^2$$
- For a $R = 1Mpc$ radius sphere, total mass of neutrino is $M_\nu \sim 10^9\, M_\odot$, $P_G \ll P_{th}$

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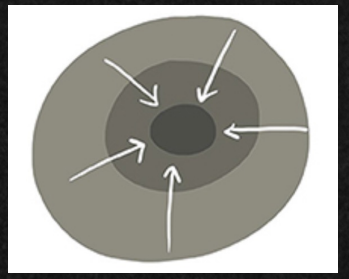

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- For a $R = 1Mpc$ radius sphere, total mass of neutrino is $M_\nu \sim 10^9\, M_\odot$, $P_G \ll P_{th}$
- Add coupling to massless ϕ, neutrino experience additional long-range force
- $$G' = \frac{g^2}{4\pi m_\nu^2},\ P_{G'} \gtrsim P_{th} \text{ if } G' \gtrsim 10^6 G$$
- Statement: nonlinear bound state of neutrinos (νhalos) can form if long-range self-interaction is too strong compared to gravity

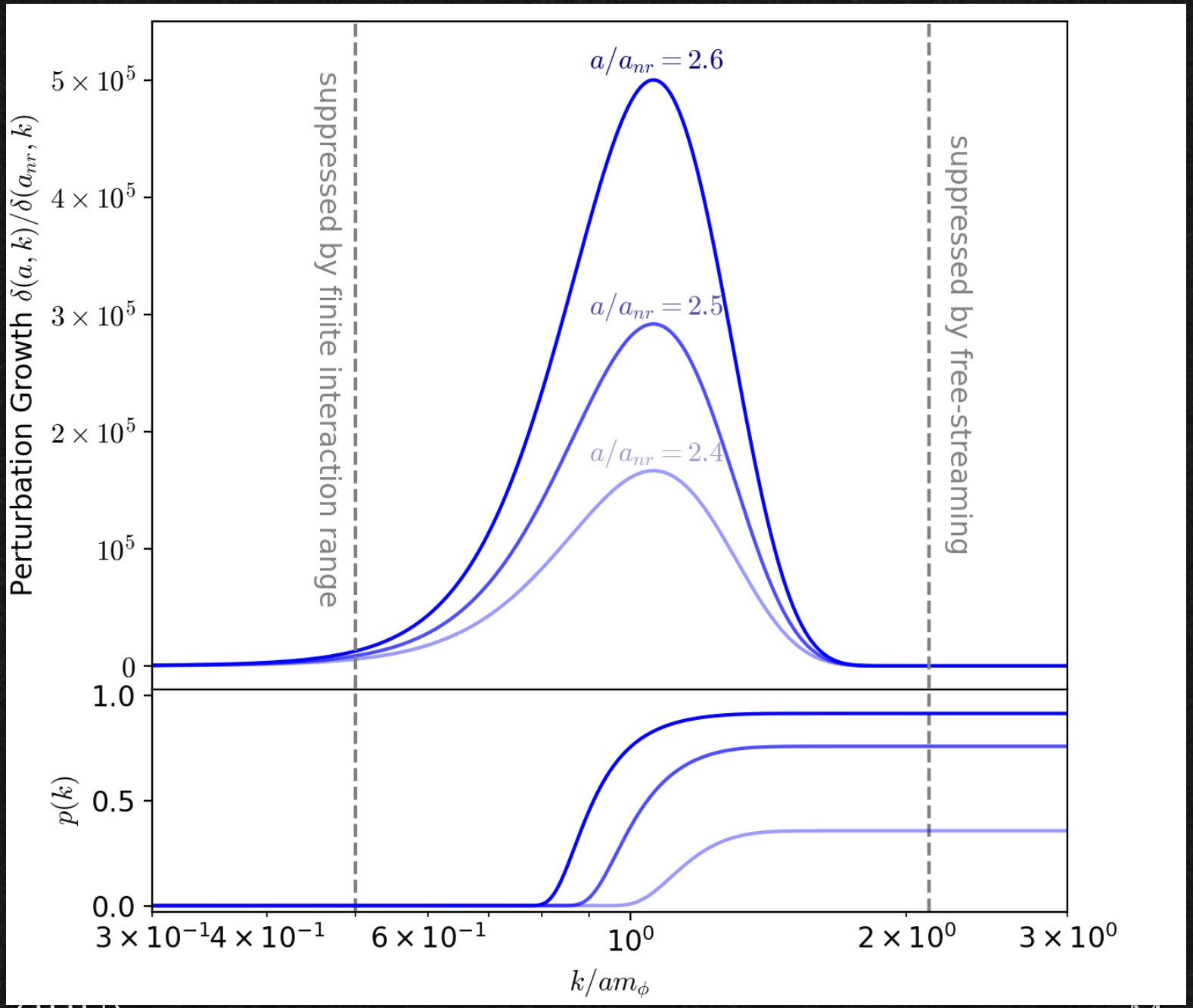
Model Setup

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

- Regime of interest:
  - Coherent interaction: $m_\phi \ll n_\nu^{1/3}$
  - No short distance physics: $g \ll 10^{-8}$, early universe unchanged
- Well defined EoMs in the linear regime [Esteban:2021, Archidiacono:2022 …]
  - Background evolution (analytical ✓ CLASS ✓)
  - Linear perturbation theory (analytical ✓ CLASS ✓)
  - Significant enhancement of neutrino perturbation ($\delta_\nu \gtrsim 1$)
  - Formation of nonlinear bound states (νhalos)

Formation of νhalos

- Long-range self-interaction in fluid approximation
- $$\ddot{\delta}_\nu + 2H\dot{\delta}_\nu = \frac{3}{2}H^2\left[\left(1+\frac{G'}{G}\frac{k^2}{k^2+a^2m_\phi^2}\right)\Omega_\nu\delta_\nu - \frac{k^2}{k_{fs}^2}\delta_\nu + \Omega_{cdm}\delta_{cdm}\right]$$
- Very fast growth mode $\delta_\nu \propto a^{\sqrt{\frac{3\Omega_\nu G'}{2\ G}}} \gg a$ at $\frac{k}{a} \gtrsim \mathrm{m}_\phi$, $\delta_\nu \sim 1$ within one Hubble time
- Scale dependent growth: exponentially suppressed at $\frac{k}{a} \lesssim \mathrm{m}_\phi$
- Similar behavior found from CLASS
- Peaked structure formation at $\frac{k}{a} \sim m_\phi$ based on Press–Schechter formalism


Perturbation Growth $\delta(a,k)/\delta(a_{nr},k)$
5×10^5
4×10^5
3×10^5
2×10^5
10^5
0
$a/a_{nr}=2.6$
$a/a_{nr}=2.5$
$a/a_{nr}=2.4$
suppressed by finite interaction range
suppressed by free-streaming
1.0
0.5
0.0
$p(k)$
3×10^{-1}
4×10^{-1}
6×10^{-1}
10^0
2×10^0
3×10^0
k/am_ϕ

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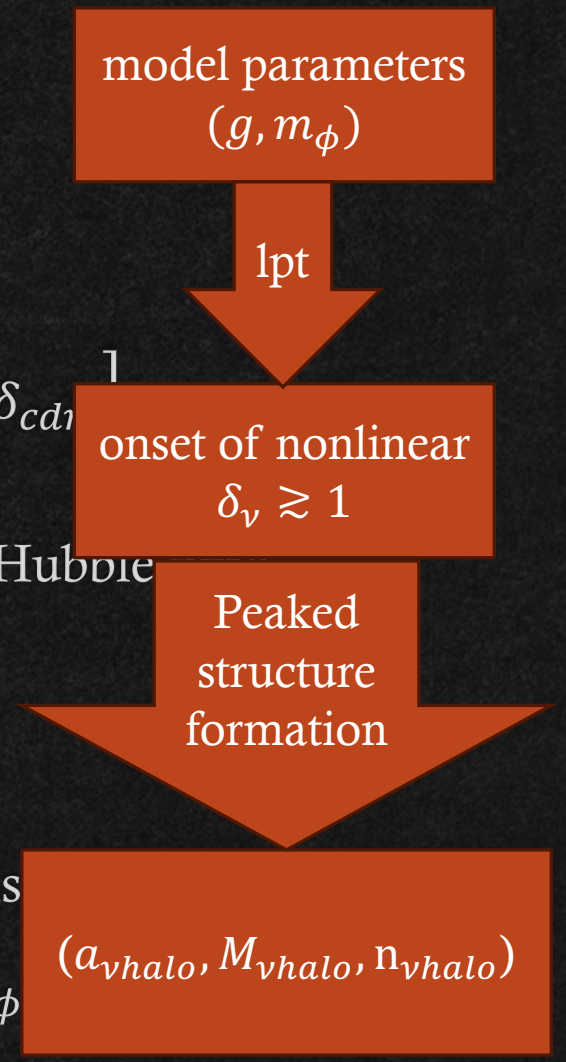
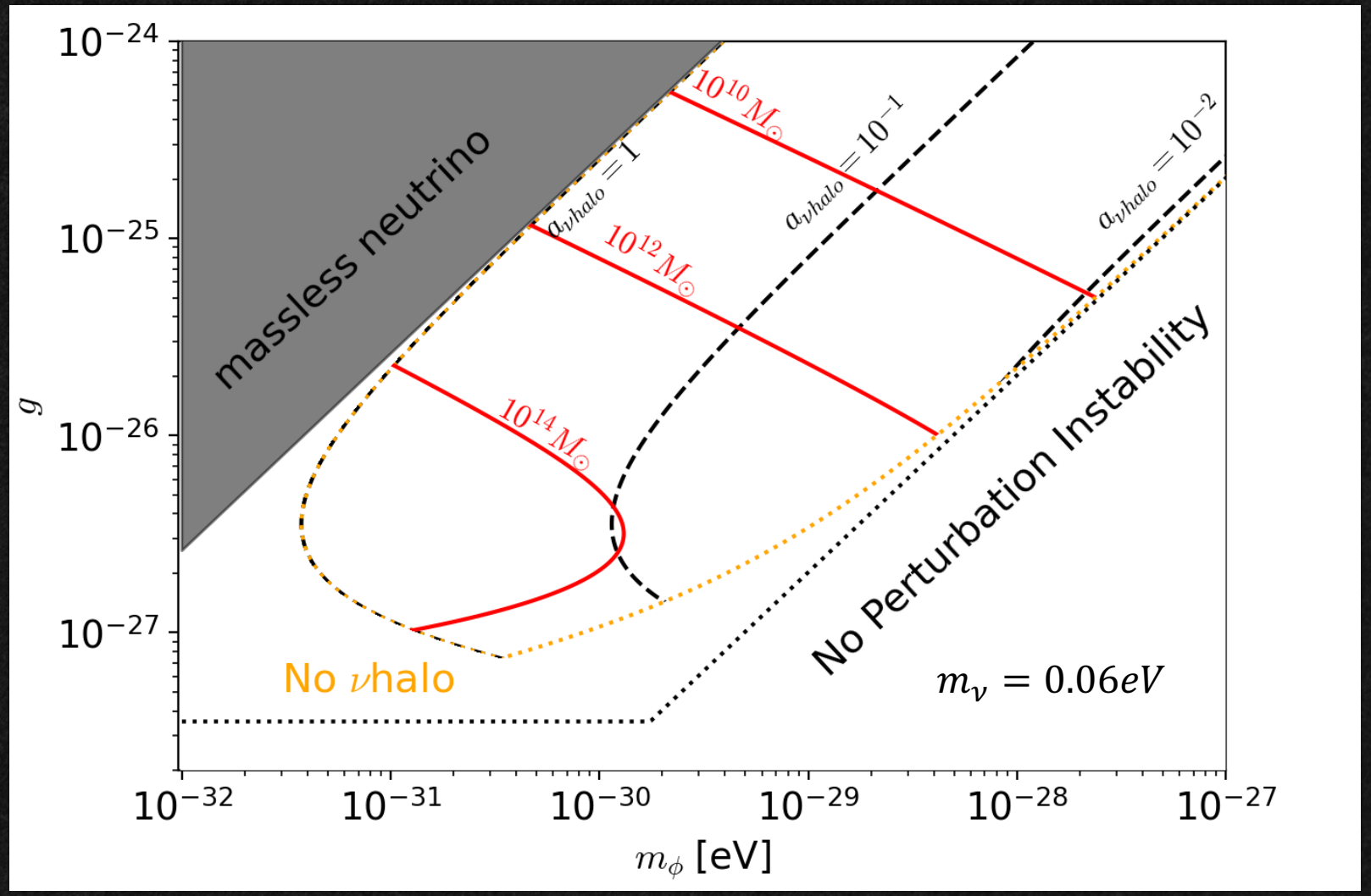


Formation of νhalos

- Very significant structure formation from neutrinos
- $M_{\nu\text{halo}} \lesssim 10^{15} M_\odot$
- $a_{\nu\text{halo}}$: $1 \sim 0.01$

  ($v_\nu < 1$ is required)
- But $\Omega_\nu \sim 0.5\%$
- How do we observe them?



Impact on matter power spectrum

- Massive primordial black hole can enhance structure formation even with small abundance ([Afshordi:2003, Carr:2018, Inman:2019, Liu:2022]) $P_{pbh} = 1/\bar{n}$
- $\nu halos$ are similar to massive pbhs at large scales
  - νhalos are bounded structure with size $r_{\nu halo} \sim 600kpc(\frac{m_\phi}{10^{-29}eV})^{-1}$, effectively a point mass at large scales
  - We assume the distribution of νhalos are uncorrelated at scale larger than interaction range
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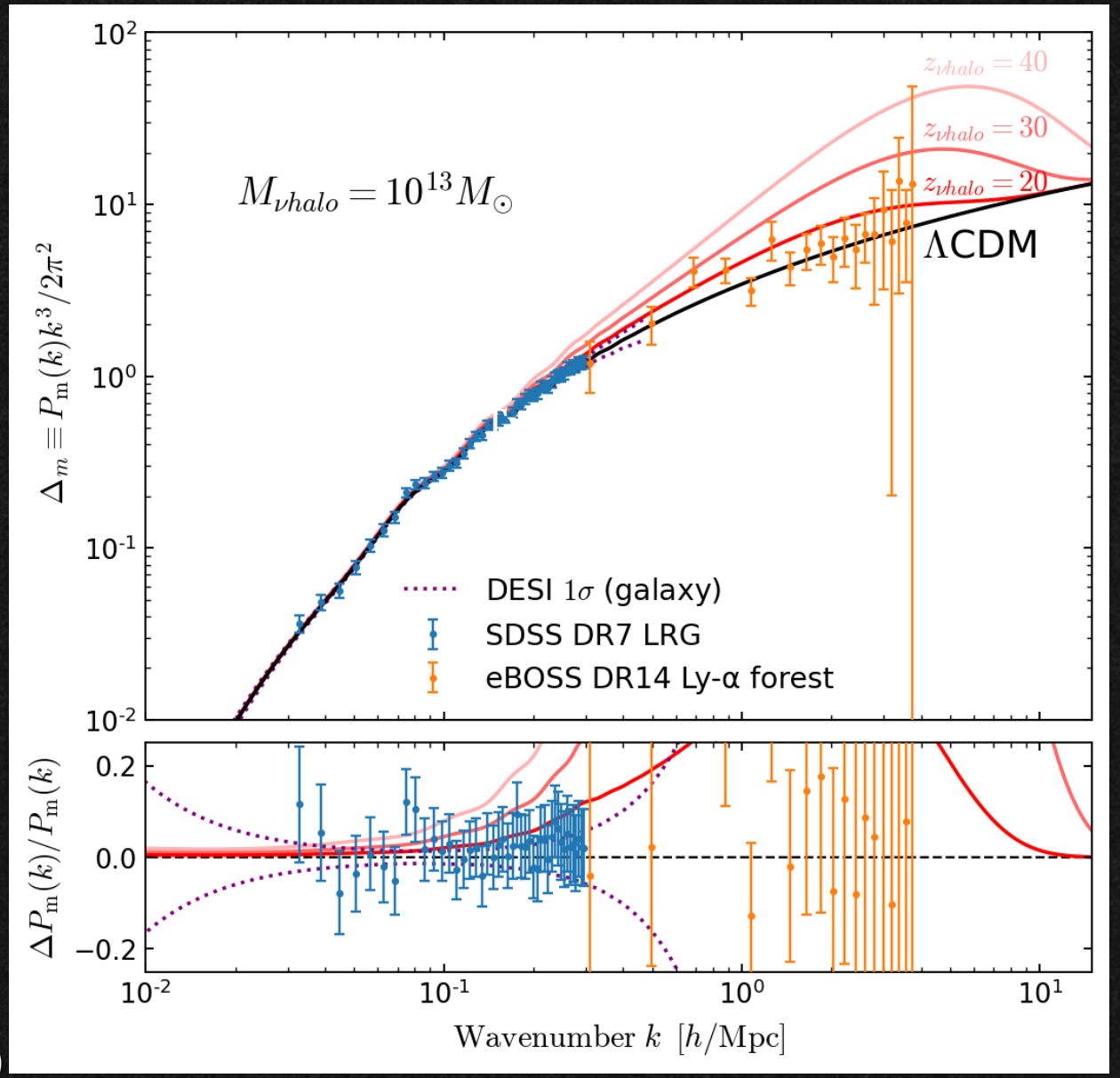
  - We assume the distribution of νhalos are uncorrelated at scale larger than interaction range
  - Distribution of νhalos are uncorrelated with dm (isocurvature)
- $$P_m(a) = D_+(a, a_{\nu halo})^2(1-\Omega_\nu)^2 P_{cc}(a_{\nu halo}) + D_+(a, a_{\nu halo})^2 \Omega_\nu^2 P_{\nu\nu}(a_{\nu halo})$$
- $$P_{\nu\nu} = 1/\bar{n}_{\nu halo}$$
- corrections need to be added at small scales

Results

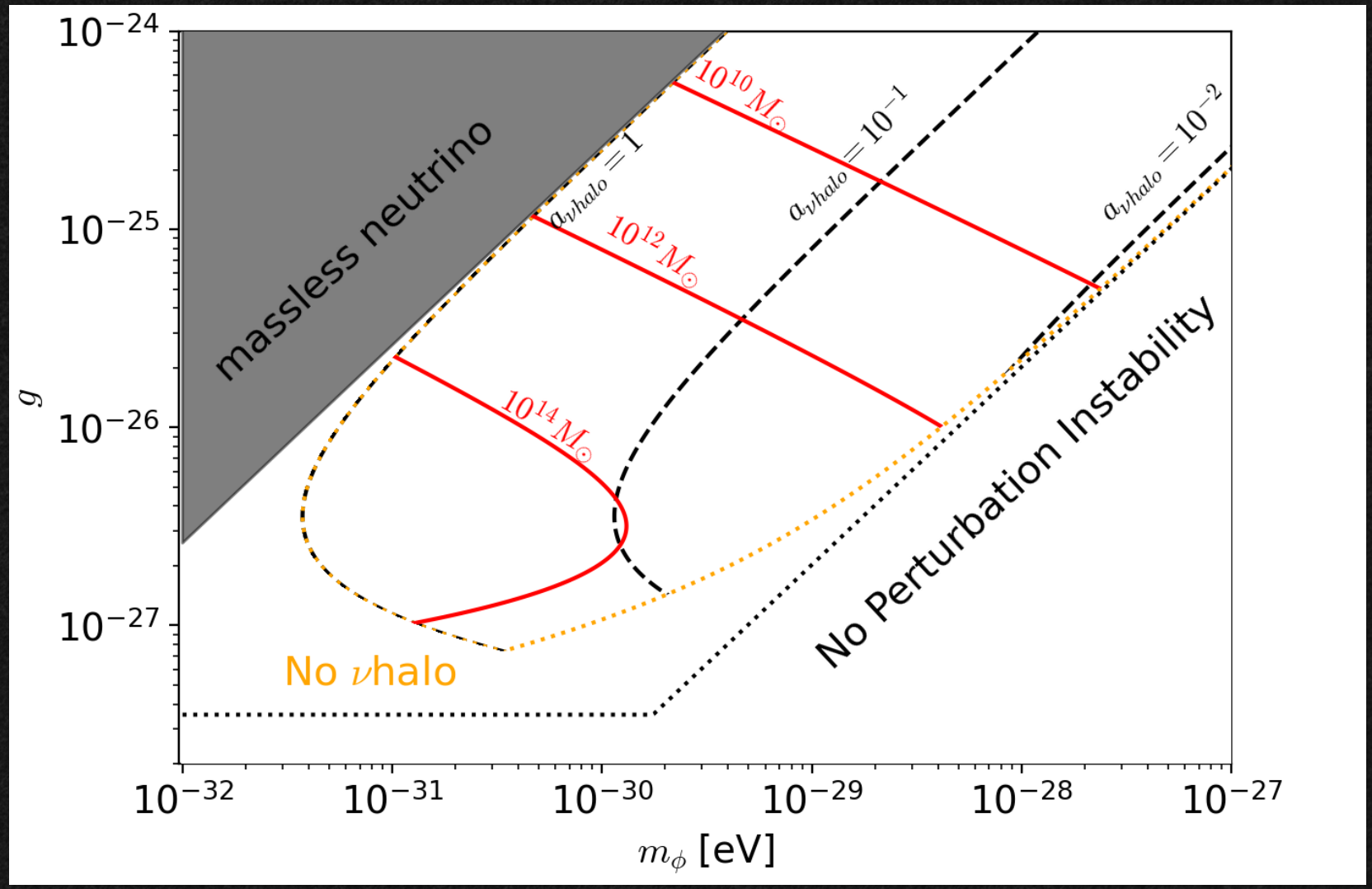
Why $O(1)$ effect on P_m is expected from $\Omega_\nu \approx 0.5\%$?

$\delta_\nu \sim 1 \gg \delta_{cdm}$, at $z \sim 100$

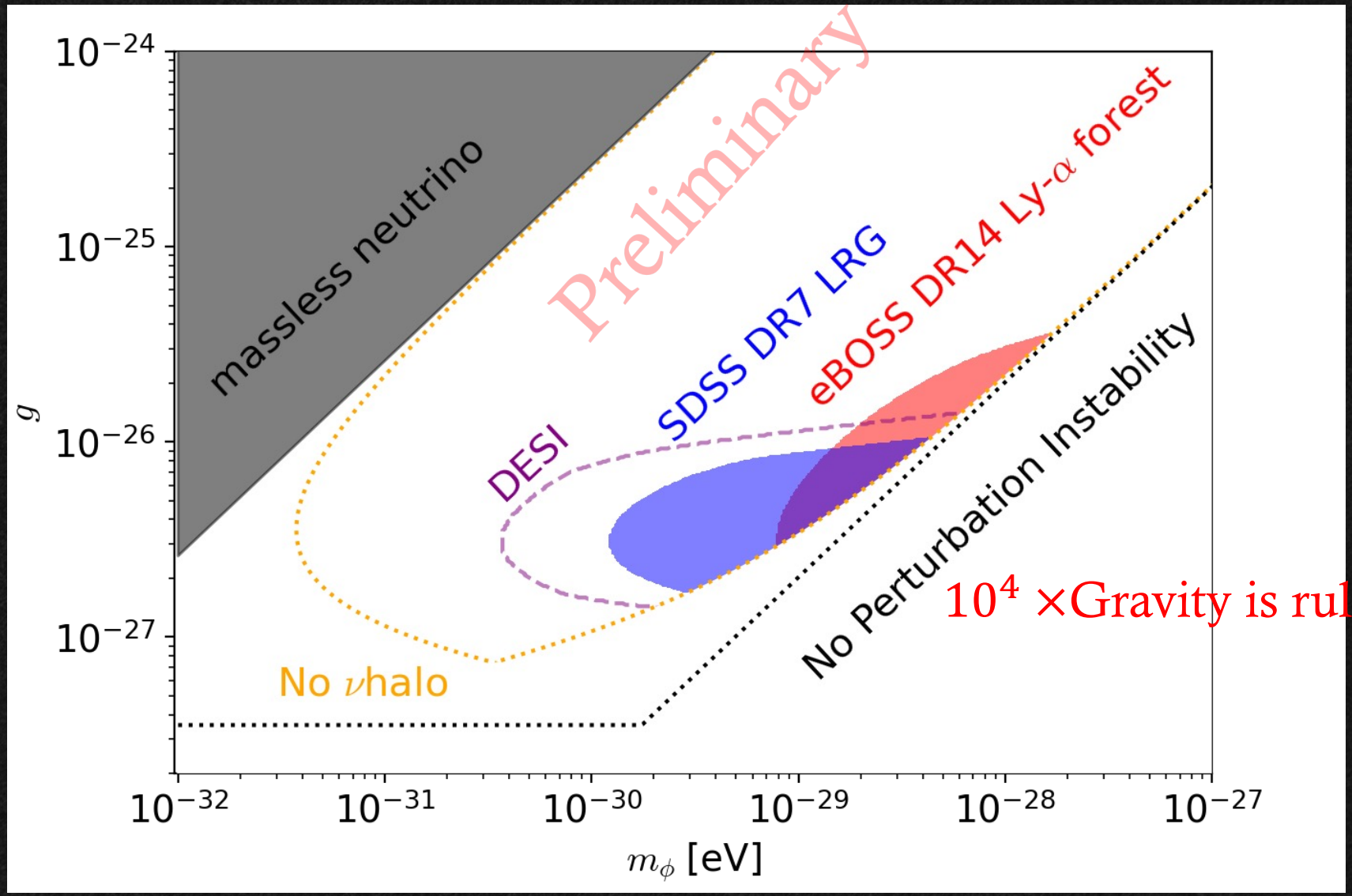
$\rho_\nu \delta_\nu \sim \rho_{cdm} \delta_{cdm}$



Results


massless neutrino
$10^{10} M_\odot$
$10^{12} M_\odot$
$10^{14} M_\odot$
$a_{\nu halo} = 1$
$a_{\nu halo} = 10^{-1}$
$a_{\nu halo} = 10^{-2}$
No νhalo
No Perturbation Instability
g
m_ϕ [eV]
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-32}
10^{-31}
10^{-30}
10^{-29}
10^{-28}
10^{-27}

Results


Preliminary
massless neutrino
DESI
SDSS DR7 LRG
eBOSS DR14 Ly-α forest
No νhalo
No Perturbation Instability
10^4 ×Gravity is ruled out!
10^{-24}
10^{-25}
10^{-26}
10^{-27}
g
10^{-32}
10^{-31}
10^{-30}
10^{-29}
10^{-28}
10^{-27}
m_ϕ [eV]

Summary

- Drastic impact on cosmic neutrino background from very simple extension of neutrino sector
- Early formation of massive bound states
- Significant impact on the matter power spectrum, scale dependent

- Potential cleaner argument in the DESI era: non free-streaming neutrino = ruled out

Thanks!