Title: Probing Long-Range Force Between Neutrinos from Cosmic Structures

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Abstract:

The long-range force between neutrinos is poorly constrained. In the late-time universe, a long-range force that is a few orders of magnitude stronger than gravity can induce Jeans perturbation instability in the non-relativistic cosmic neutrino background, drastically changing its large-scale behavior. In this talk, I will describe how the cosmic neutrino background evolves and forms nonlinear bound states in the presence of a long-range force. I will then discuss the impact of these neutrino bound states on the matter structures in the universe, and the constraints due to the absence of these signals.

Probing Long-Range Force Between Neutrinos from Cosmic Structures

Xuheng Luo

Johns Hopkins University

with David E. Kaplan, Surjeet Rajendran

Outline

- Motivation and short review
- Evolution of cosmic neutrino background in the present of a long range force
  - Perturbation instability and formation of nonlinear bound states
- Signals in cosmic structures
- Outlook and summary

How to probe long range force between neutrinos?

Why it is hard to probe

- Do not induce force between atoms
  - Unbounded by fifth force experiments
- Weakly interacts
- Nonlocal, not controlled
- Long range bound is absent
  -

- Induce fifth force between atoms
  - Bounded by fifth force experiments
- Abundantly exist in matter
- Coherent enhancement of the interaction
- strong constraints from EP tests:
  - $g_{\phi e} \lesssim 10^{-24}$ or $10^{-6} \times$ Gravity

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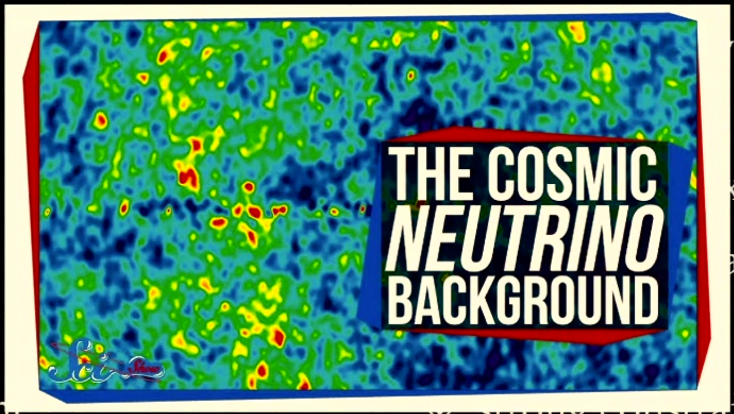

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The Cosmic Neutrino Background

- Thermal relic from early universe, most abundant source of neutrinos in the universe
- Known to be relativistic and free-streaming prior to recombination
- Become non-relativistic at around $z_{nr} \sim 120 \left(\frac{m_\nu}{0.06\ eV}\right)$
- Galaxy surveys aim to measure its gravitational effect at the late universe to measure the mass of neutrinos. → also sensitive to new physics

A short historical review

- Neutrinos bounded by Yukawa-like force ---- [Stephenson, Goldman, McKellar 1996]
- Dark energy from mass varying neutrinos ---- [Fardon, Nelson, Weiner 2003] and others
  - Nontrivial background energy density evolutions that mimic dark energy
- Instability issue with mass varying neutrinos ---- [Afshordi, Zaldarriaga, Kohri 2005]
  - Formation of non-linear bound states
- Recent:

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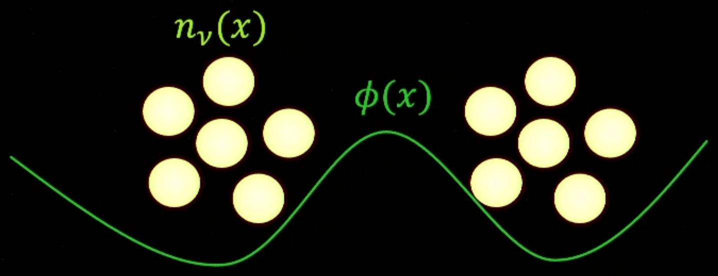
- Recent: [Esteban 2021] and this work

Setting up the cosmology…

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

- What we need: distribution of neutrinos
  - Background evolution: $\phi(z)$, $n_\nu(z)$
    - Evolution of effective neutrino mass
  - Perturbation evolution: $\delta\phi(x)$, $\delta n_\nu(x)$
    - Numerically solve Boltzmann equations ($\Psi_0 \to \delta\phi,\ \delta\phi \to \Psi_1$) → modified CLASS code (this work)
    - Can be effectively described using non-relativistic fluid approximation (this work)



Long range force induced perturbation growth

- $\ddot{\delta}_c + 2H\dot{\delta}_c = \frac{3}{2}H^2 \Big[\qquad \delta_c \qquad \Big]$
- $\delta_c \propto a$

Long range force induced perturbation growth

- $$\ddot{\delta}_\nu + 2H\dot{\delta}_\nu = \frac{3}{2}H^2\left[\left(1 + \frac{g^2}{4\pi G m_\nu^2}\frac{k^2}{k^2 + a^2 m_\phi^2}\right)\Omega_\nu \delta_\nu - \frac{k^2}{k_{fs}^2}\delta_\nu\right]$$

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- Kinetic energy (k_{fs}) vs long range force ($g,\ k_\phi \sim a m_\phi$)

- Jeans criterion: potential energy > kinetic energy ⟺ growth mode exist

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- Jeans criterion: potential energy > kinetic energy ⟺ growth mode exist

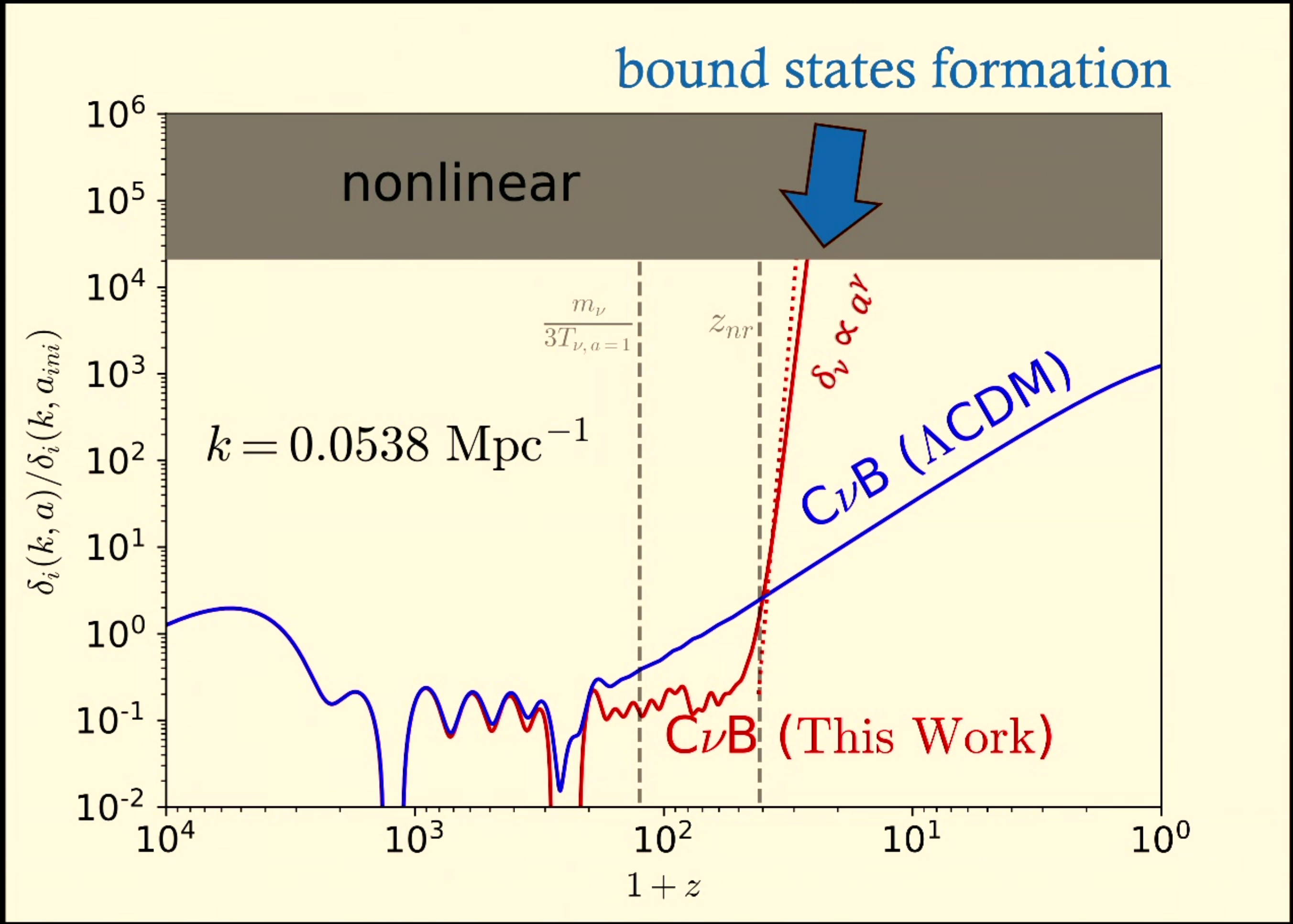
- Growth mode: $\delta_\nu \propto a^\gamma, \quad \gamma \gg 1 \quad (\gamma \propto g)$

  - Yukawa force can be stronger than gravity, the dynamical time scale is shorter than Hubble time

Perturbation evolution at k_ϕ

$\mathbf{g = 10^{-26} \sim 10^5 \times gravity}$

$\mathbf{m_\phi = 10^{-29}\ eV \sim 2\mathit{Mpc}^{-1}}$



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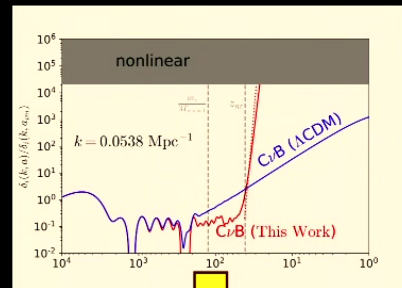
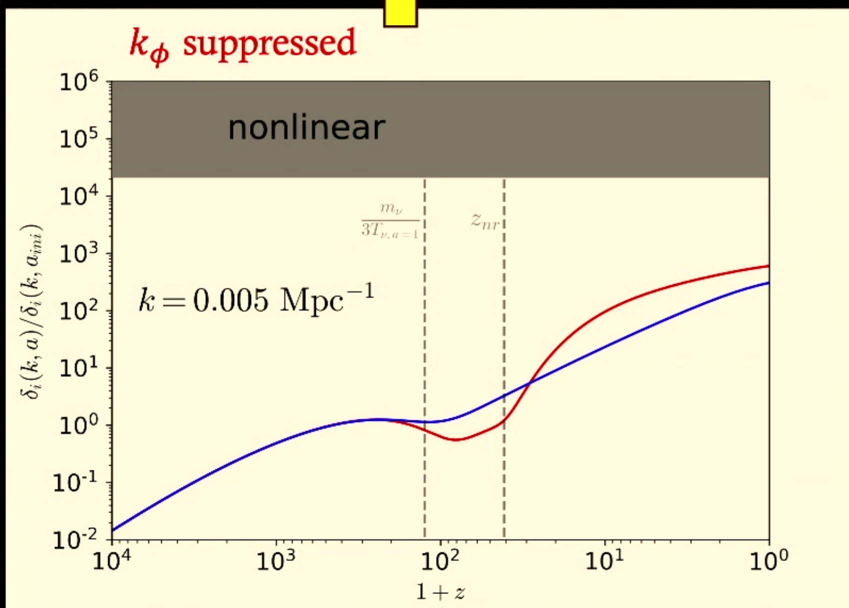
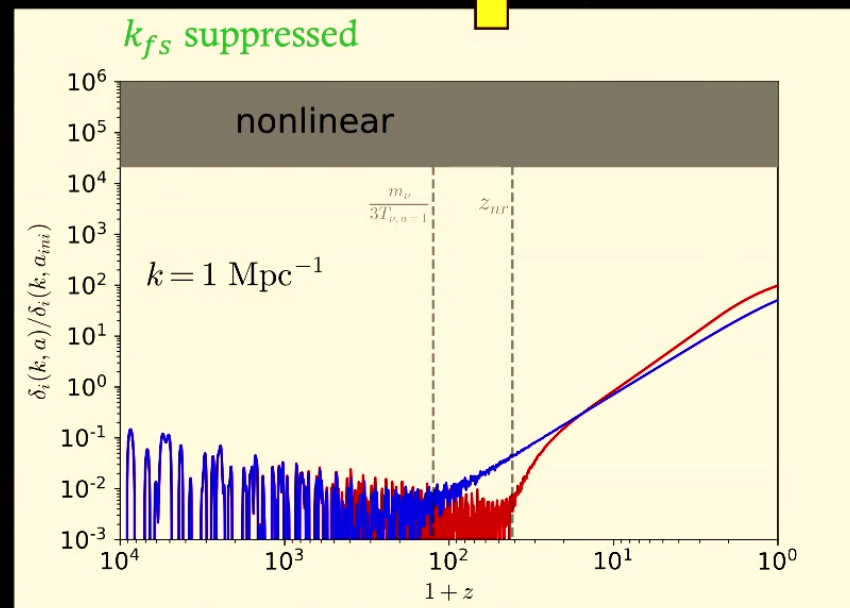
Perturbation evolution (off-peak)

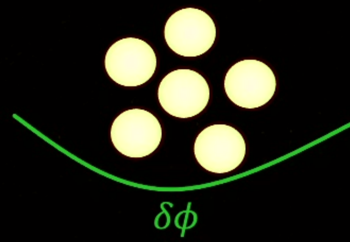


wavenumber



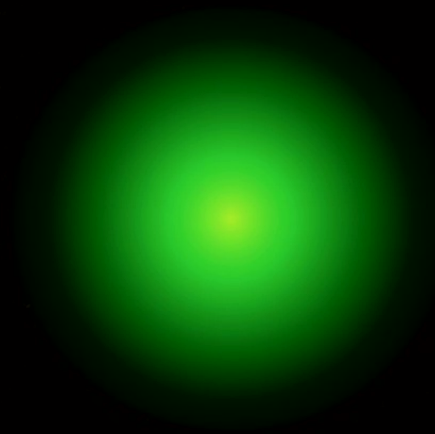


Perturbation growth



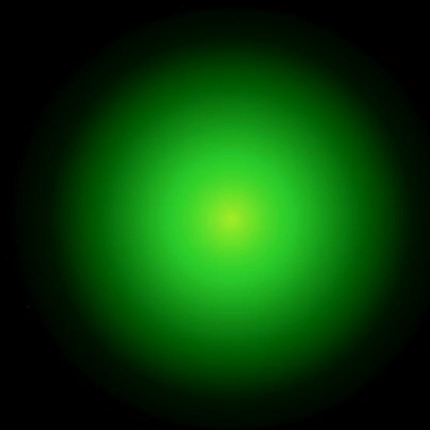
	Long range force between neutrinos	Gravity
Source?	Jeans perturbation instability	Jeans perturbation instability
Growth mode?	$\delta_\nu \propto a^\gamma, \gamma \gg 1$	$\delta_{cdm} \propto a$
Wavelength dependence?	Dependent on wavelength ◇ k_ϕ and k_{fs}	Scale independent
Outcome?	Neutrino bound states	Dark matter halo

Neutrino bound states



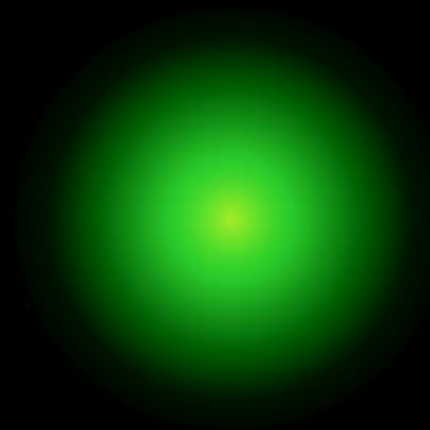
- Diffused bound states: $\rho \sim \rho_\nu(z) \sim m_\nu n_\nu(z)$

Neutrino bound states



- Diffused bound states: $\rho \sim (\frac{z}{100})^3 \ 0.01\text{GeV}/cm^3$
  - Energy fraction in matter ~ 0.45%
  - Like a diffused dark matter halo

Neutrino bound states



- Diffused bound states: $\rho \sim (\frac{z}{100})^3 \ 0.01\text{GeV}/cm^3$
  - Energy fraction in matter ~ 0.45%
  - Like a diffused dark matter halo
- Radius depend on the choice of parameters: $R \sim m_\phi^{-1}$
  - Peaked mass function in Yukawa induced structure formation, [Domenech 2023]
- Formation at when neutrino become non-relativistic
  - which depend on choice of parameters (background evolution): $z \lesssim 100$

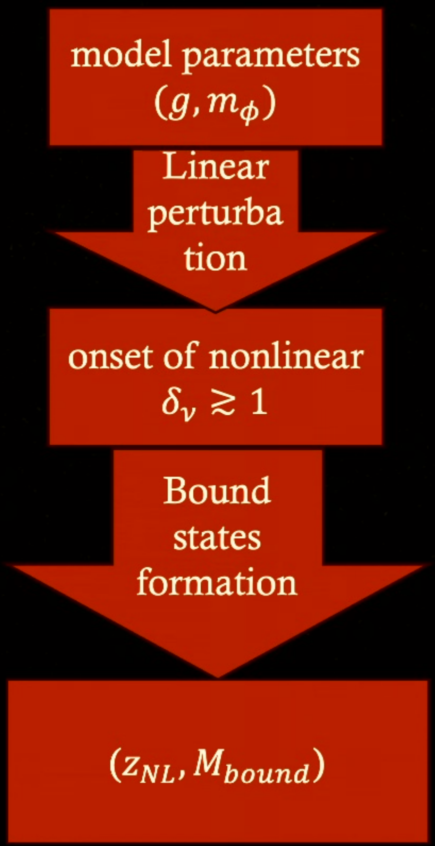
Background Evolution

- Main effect: neutrino mass is suppressed to up to certain redshift: $z_{nr}(g, m_\phi)$ [Esteban 2021]

- $$V_{eff}(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + g\phi \langle \bar{\nu}\nu \rangle$$

  - Early universe: minimum of the potential is shifted to: $m_\nu + g\phi = 0.$ → massless neutrino
  - Late universe: minimum of the potential return to: $\phi = 0.$ → neutrino become massive

- **Larger coupling g result in later formation of bound state**



model parameters
(g, m_ϕ)
Linear perturba tion
onset of nonlinear
$\delta_v \gtrsim 1$
Bound states formation
(z_{NL}, M_{bound})

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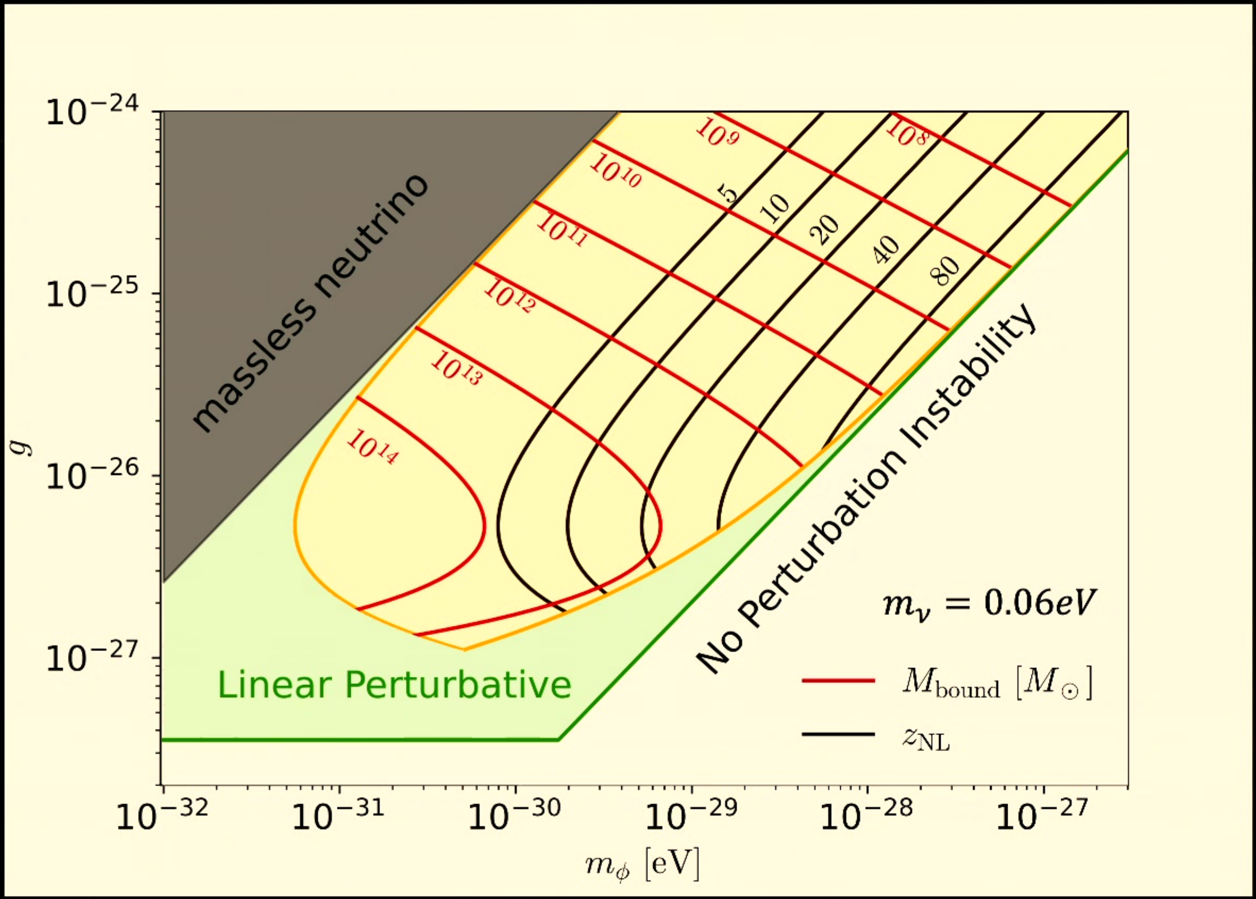

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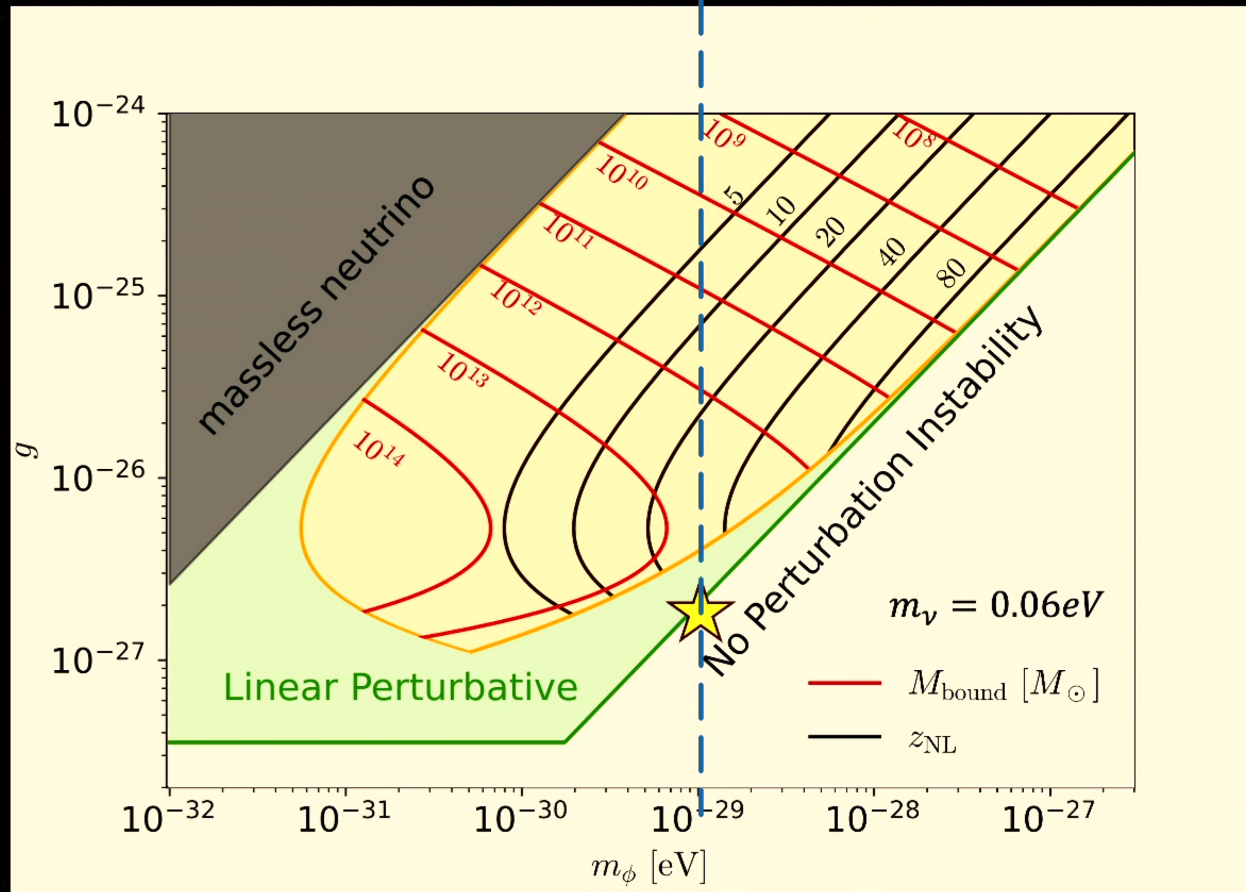

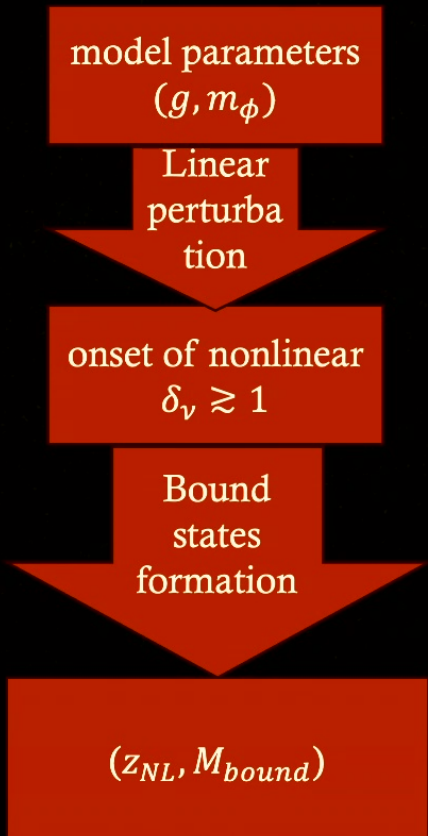
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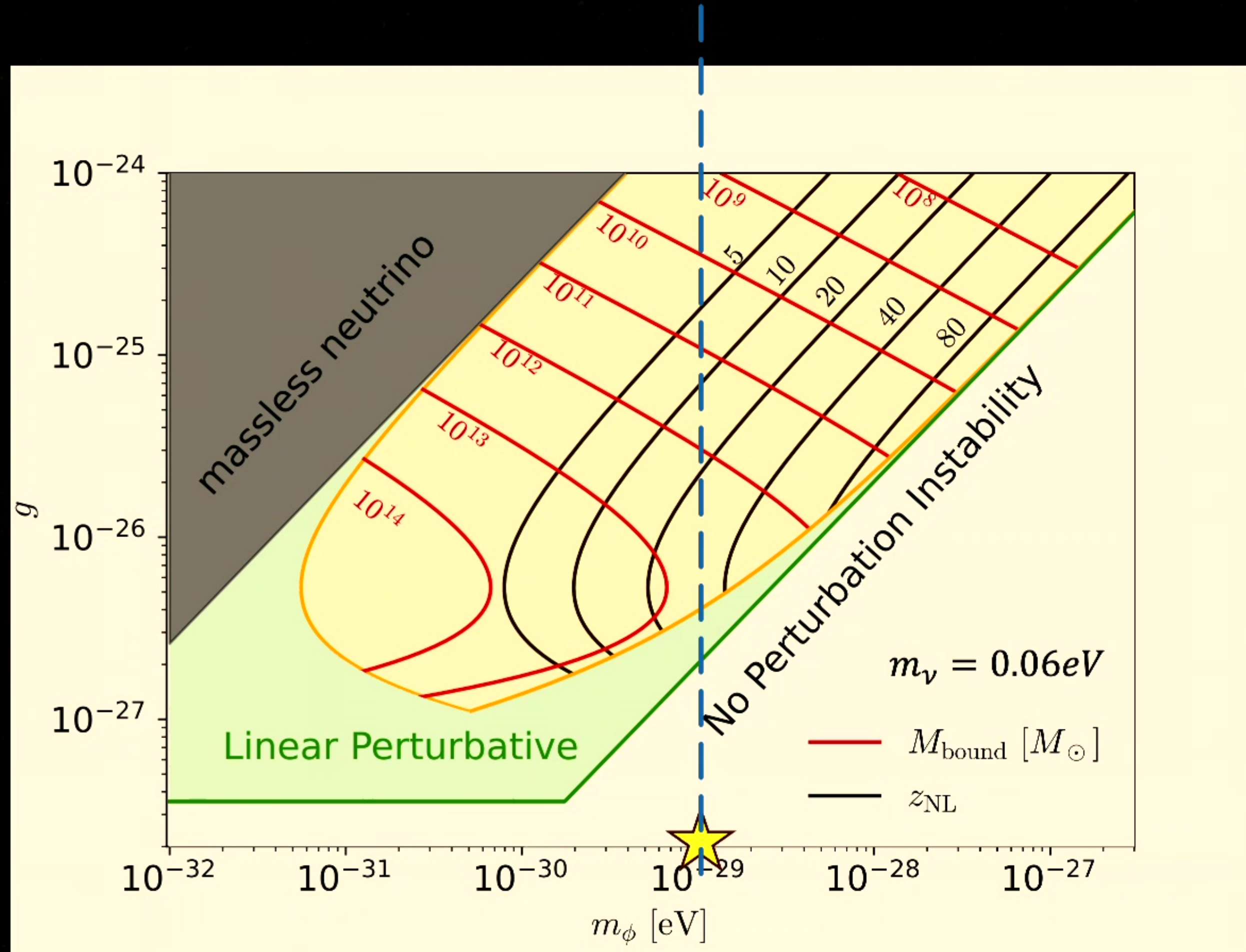
massless neutrino
Linear Perturbative
No Perturbation Instability
$m_\nu = 0.06eV$
$M_{\rm bound}\ [M_\odot]$
$z_{\rm NL}$
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{8}
5
10
20
40
80
10^{-24}
10^{-25}
10^{-26}
10^{-27}
g
10^{-32}
10^{-31}
10^{-30}
10^{-29}
10^{-28}
10^{-27}
m_ϕ [eV]

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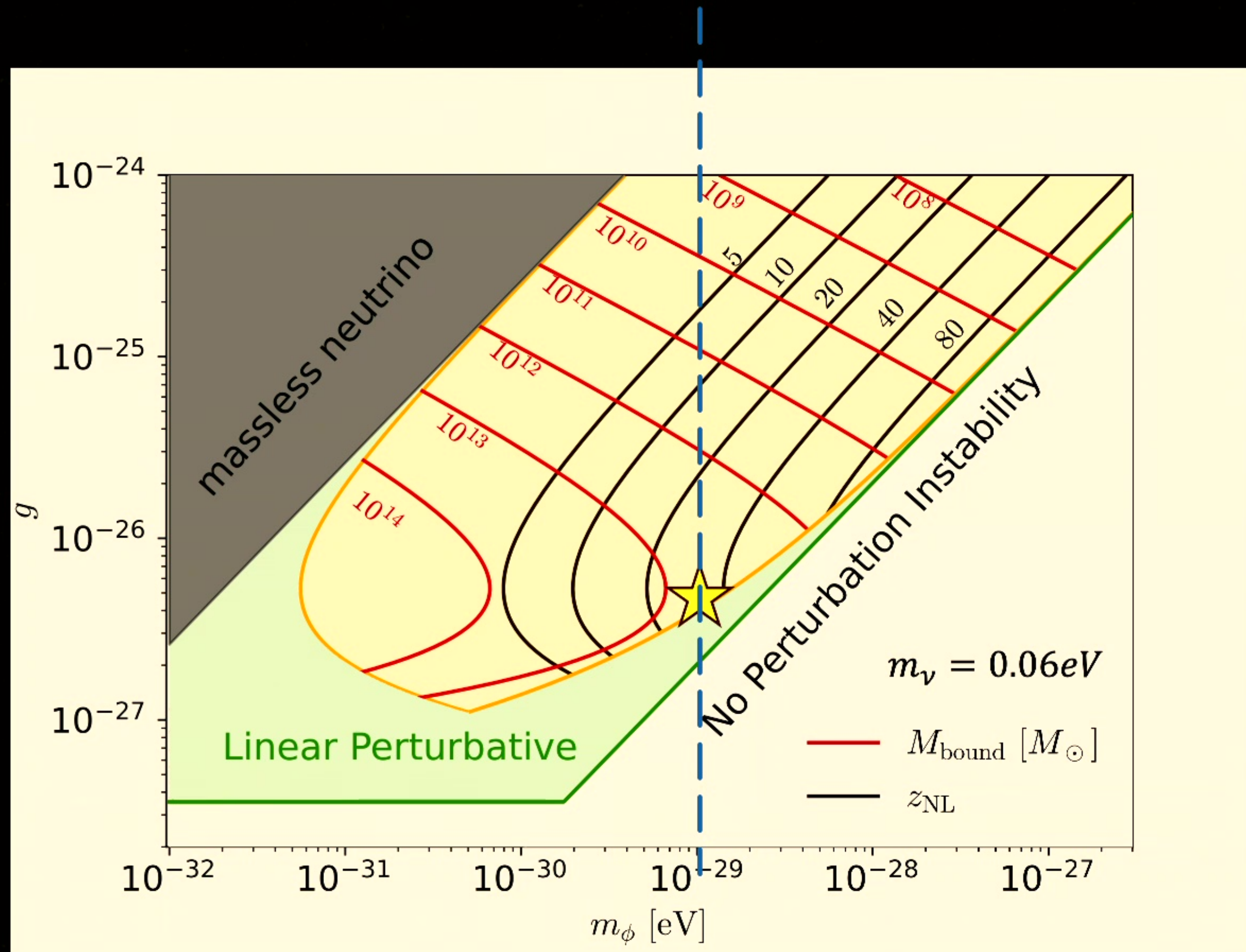

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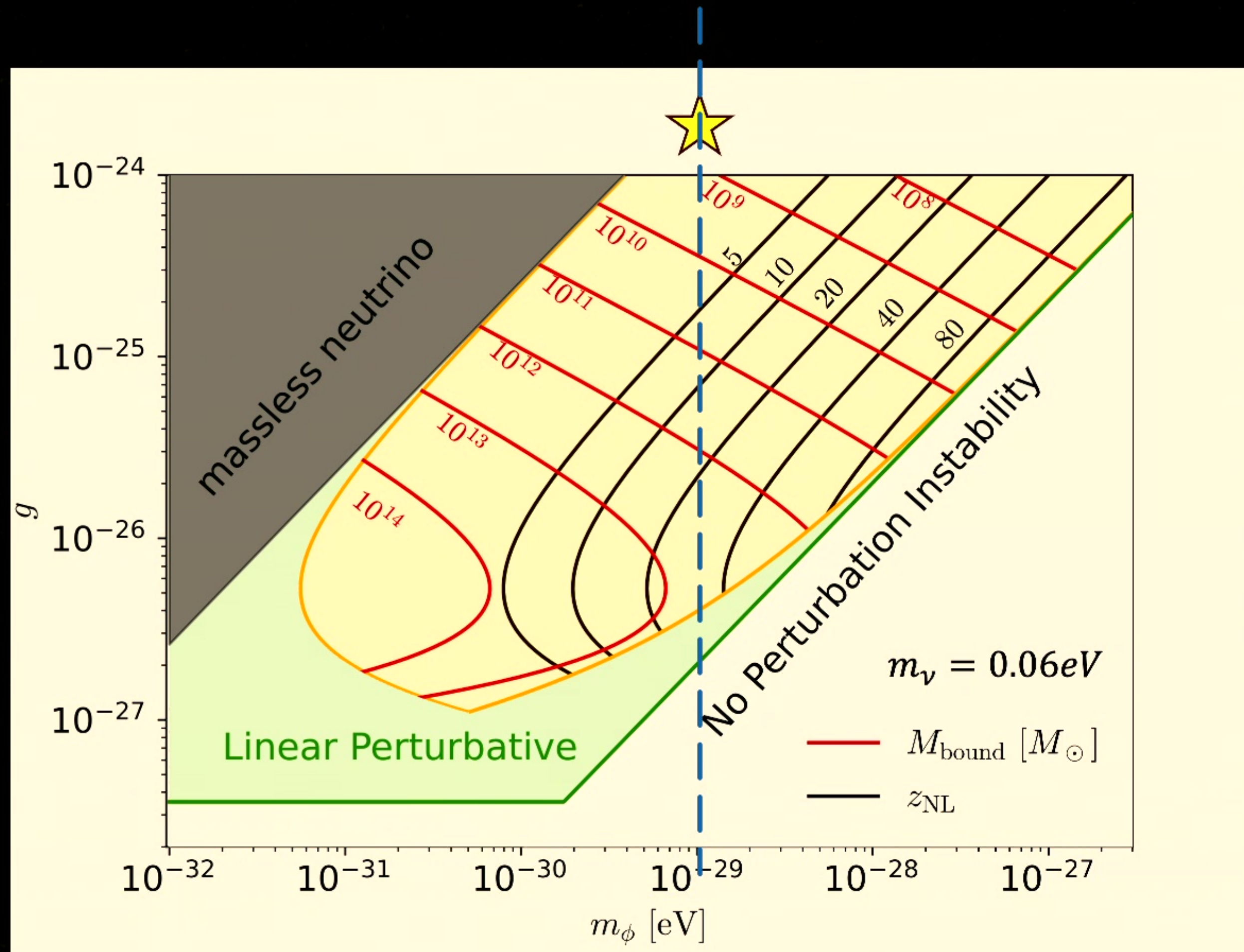
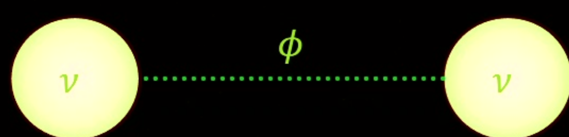


~~How to probe long range force between neutrinos?~~

How to probe neutrino bound states?



ΛCDM Universe

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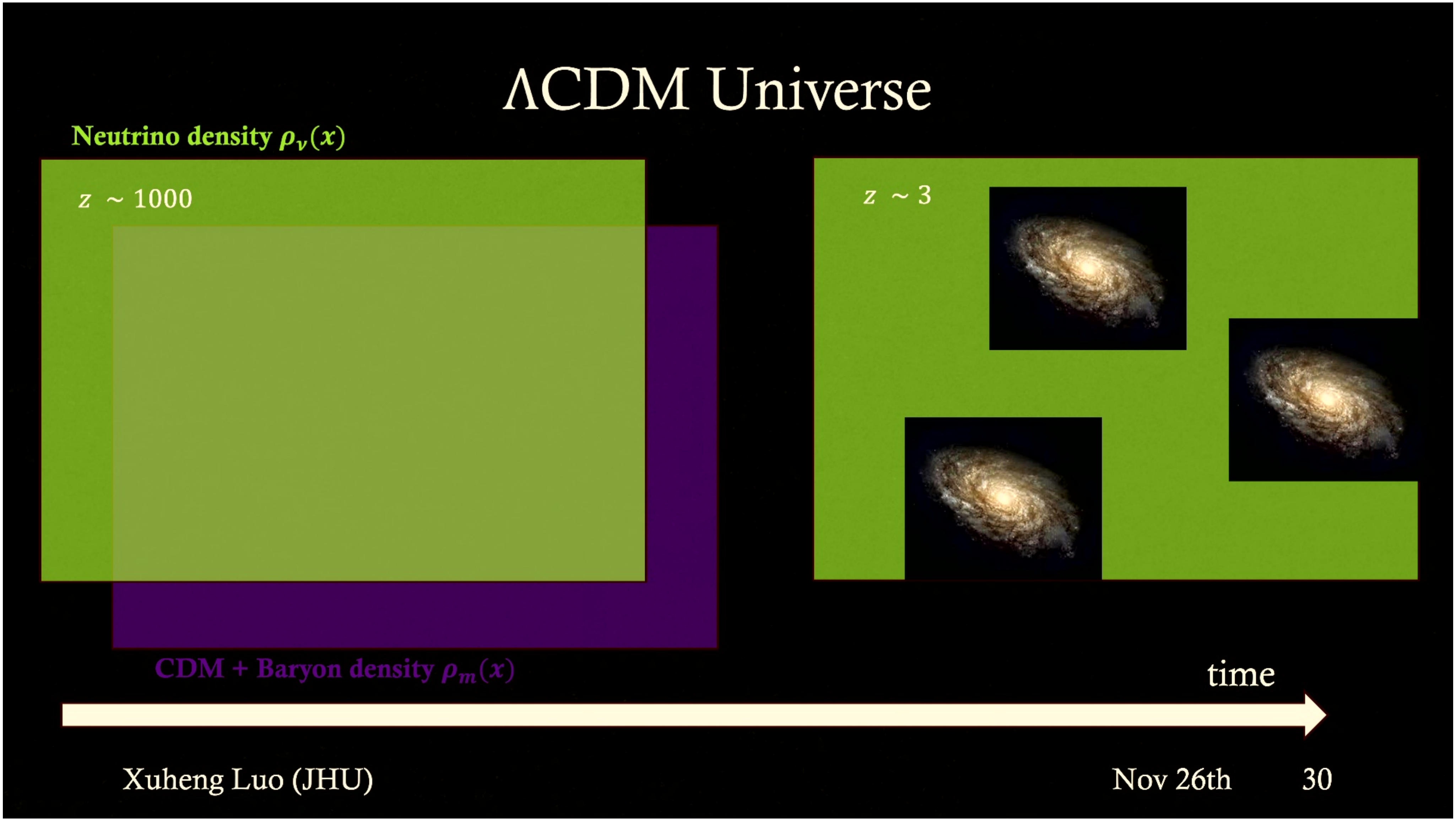

ΛCDM Universe
Neutrino density $\rho_\nu(x)$
$z \sim 1000$
$z \sim 3$
CDM + Baryon density $\rho_m(x)$
time
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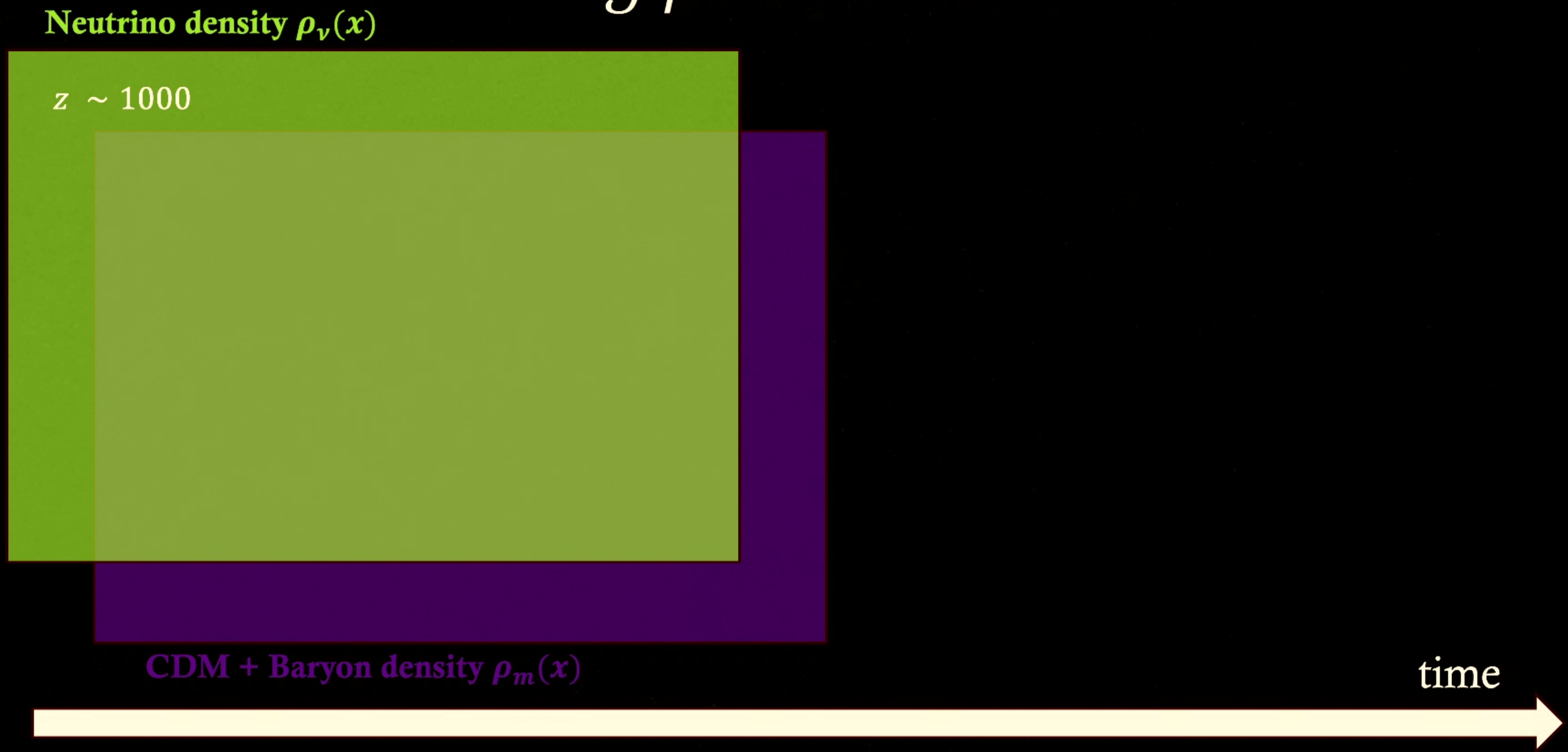
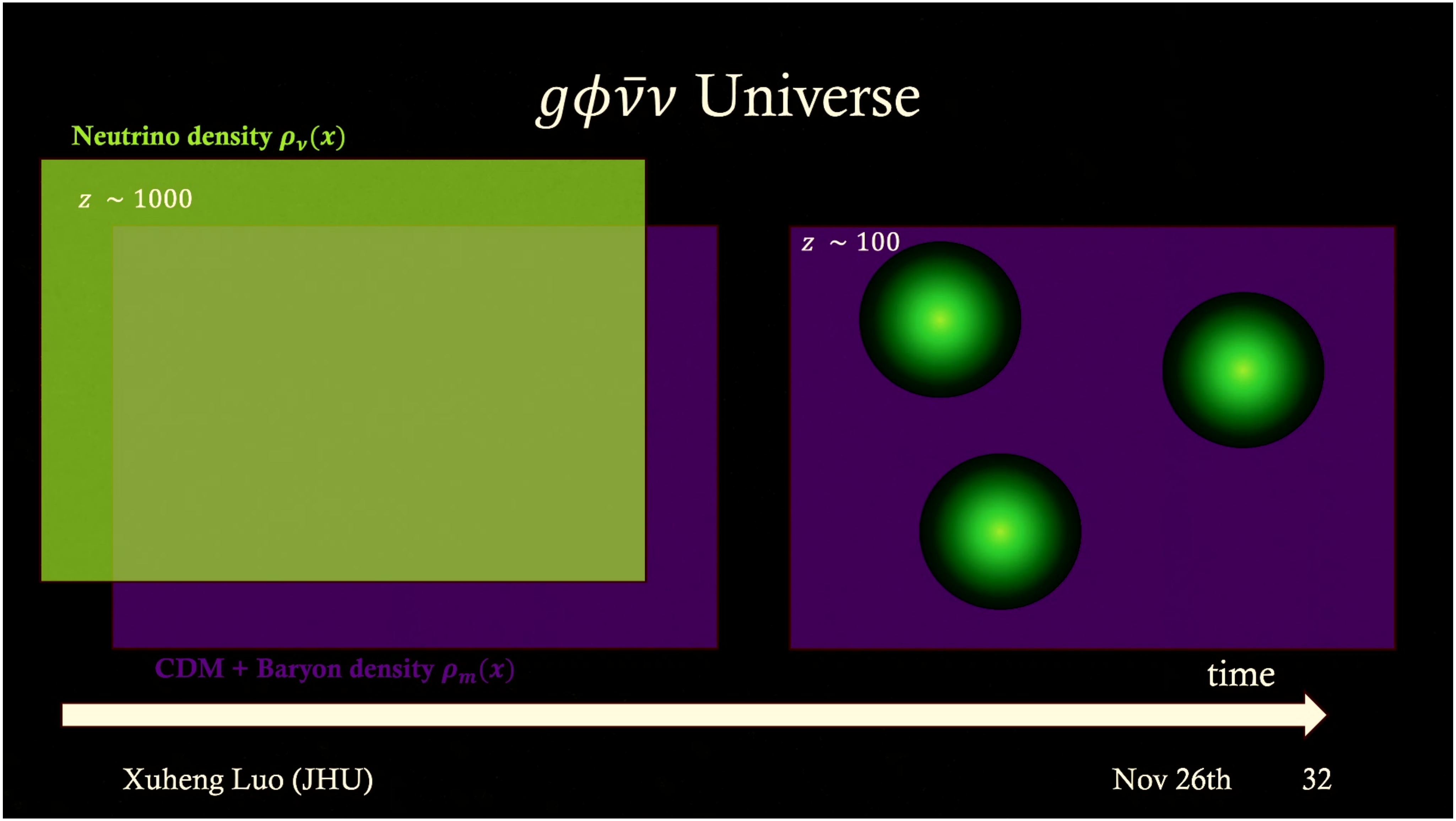
30

$g\phi\bar{\nu}\nu$ Universe




$g\phi\bar{\nu}\nu$ Universe
Neutrino density $\rho_\nu(x)$
$z \sim 1000$
$z \sim 100$
CDM + Baryon density $\rho_m(x)$
time
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32

How to quantify the impact

- Linear perturbation theory for CνB break down
- Smooth CνB become many diffused clumps of matter
  - From linear perturbation theory: z_{NL}, M_{bound}, etc

How to quantify the impact

- Linear perturbation theory for CνB break down
- Smooth CνB become many diffused clumps of matter
  - From linear perturbation theory: z_{NL}, M_{bound}, etc
- Gravitational impact on matter perturbation (matter power spectrum)
- Hosting non-standard baryonic structure (early star formation)

Perturbation sources

- Matter power spectrum is just counting number of objects …

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Perturbation sources

- Matter power spectrum is just counting number of objects …
- Discrete distribution of neutrinos will (minimally) contribute to the power spectrum as

$$\Delta P_m \propto \frac{1}{\bar{n}_{bound}}$$

Perturbation sources

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$$\Delta P_{m,\,iso} = \frac{f_\nu^2 D_+^2(a_{NL})}{\bar{n}_{bound}}$$

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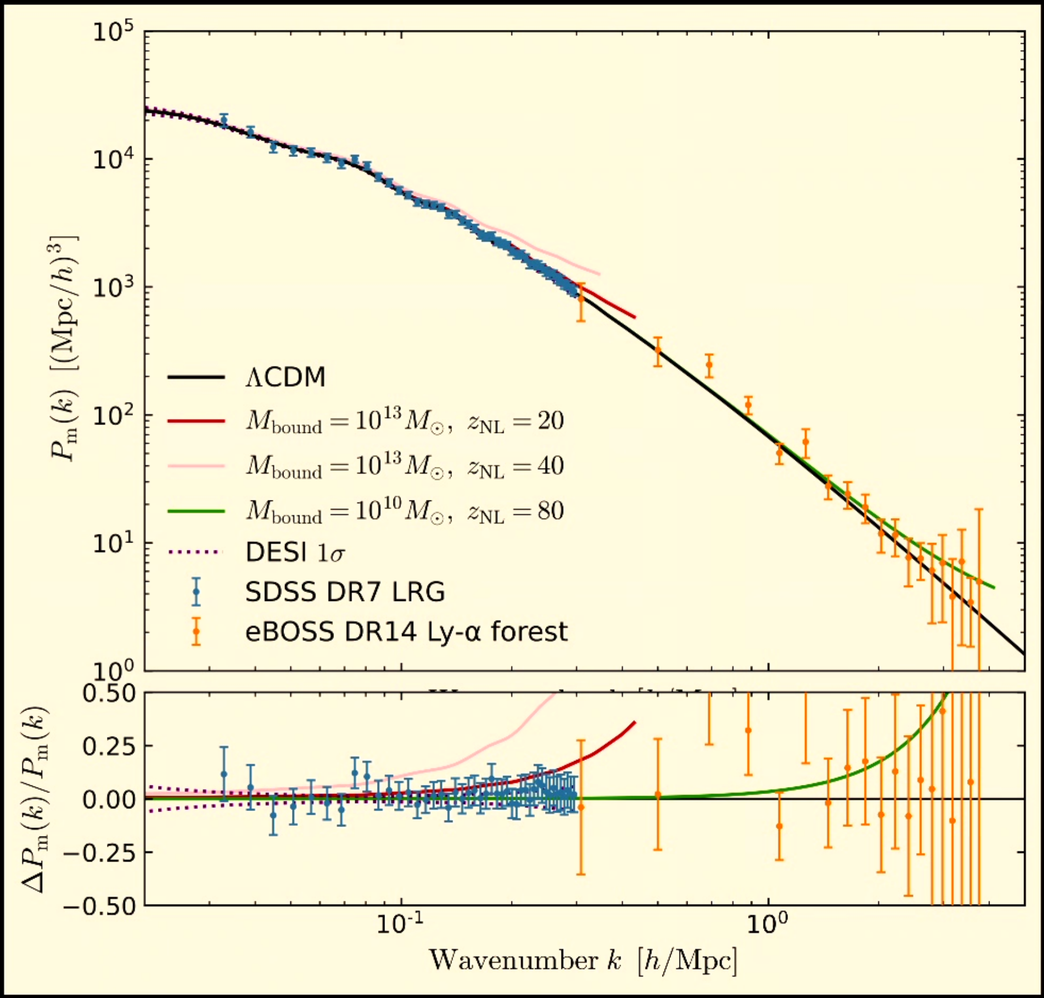
- Discrete distribution of neutrinos will (minimally) contribute to the power spectrum as

$$\Delta P_{m,\,iso} = \frac{f_\nu^2 D_+^2(a_{NL})}{\bar{n}_{bound}}$$

- Very blue tilted, need to clarify the cut-off scale
  - Matter perturbation will collapse around the source: minihaloes
  - We only use linear part of the power spectrum, applied small scale cutoff: $\Delta P_m = 0$ at $k \gtrsim \bar{r}_{minihalo}^{-1}$

Matter power spectrum

- well measured at $k \sim 0.1/Mpc$, $\mathcal{O}(1\%)$
- Okay sensitivity at $k \sim 1/Mpc$, $\mathcal{O}(10\%)$
- Enough to resolve neutrino bound states



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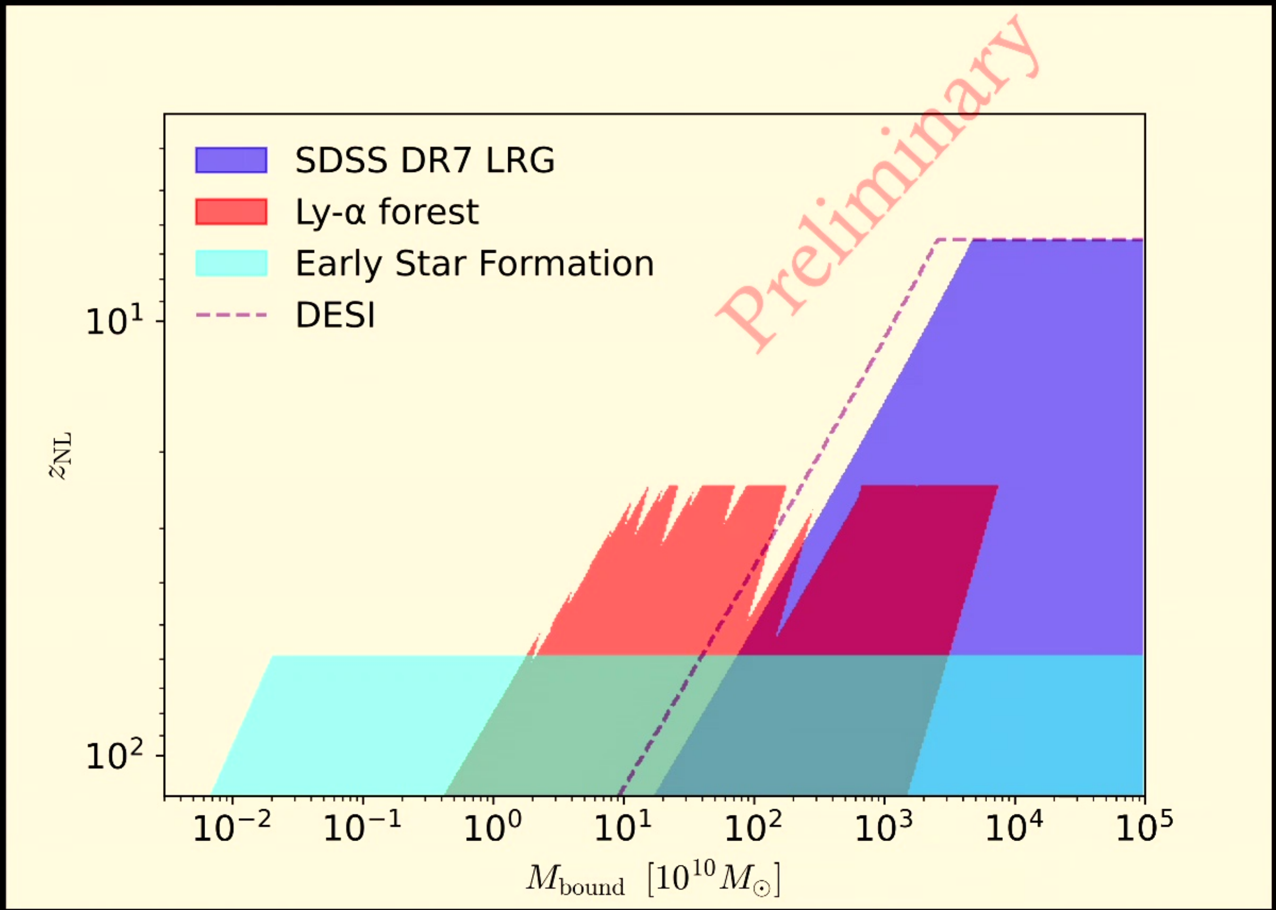
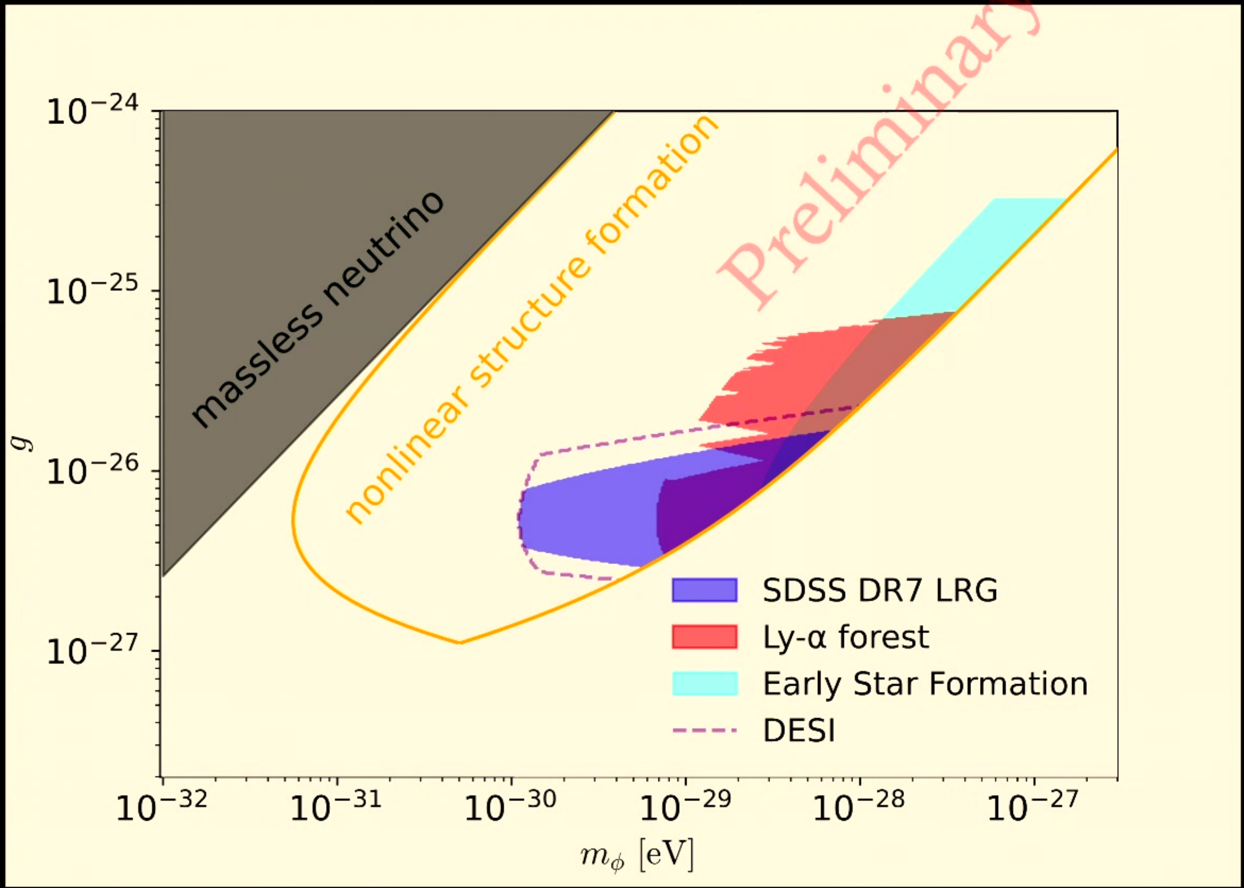
Baryonic Structure (star formation)

- In ΛCDM universe, massive halo will capture baryons and lead to star formation
- Star formation is a runaway process if cooling time scale is short than dynamical timescale (ROS)
- If atomic hydrogen cooling is active ($M_{\rm bound} \gtrsim 10^8\ M_\odot$) , the cooling is very efficient (~Myr)
- Early formation of stars can alter the reionization history ($z \sim 7$)

Constraints (bound states formation)



Constraints ($g\phi\bar{\nu}\nu$)



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Summary

- Bound states of CνB can form from long range force between neutrinos
- Massive neutrino bound states can have significant impact on matter structures
- Potential impact on neutrino experiments and dm substructure search
- All these can be accomplished by a minimum extension to the neutrino sector

Thank you!