Probing Neutrino Self-Interactions Using JWST Data

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Introduction & Motivation

Standard Model (SM) in Particle Physics is successful in explaining various phenomena

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But Beyond Standard Model (BSM) exists!!! E.g., Neutrinos have mass.

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There are a number of new interactions possible in BSM theories.

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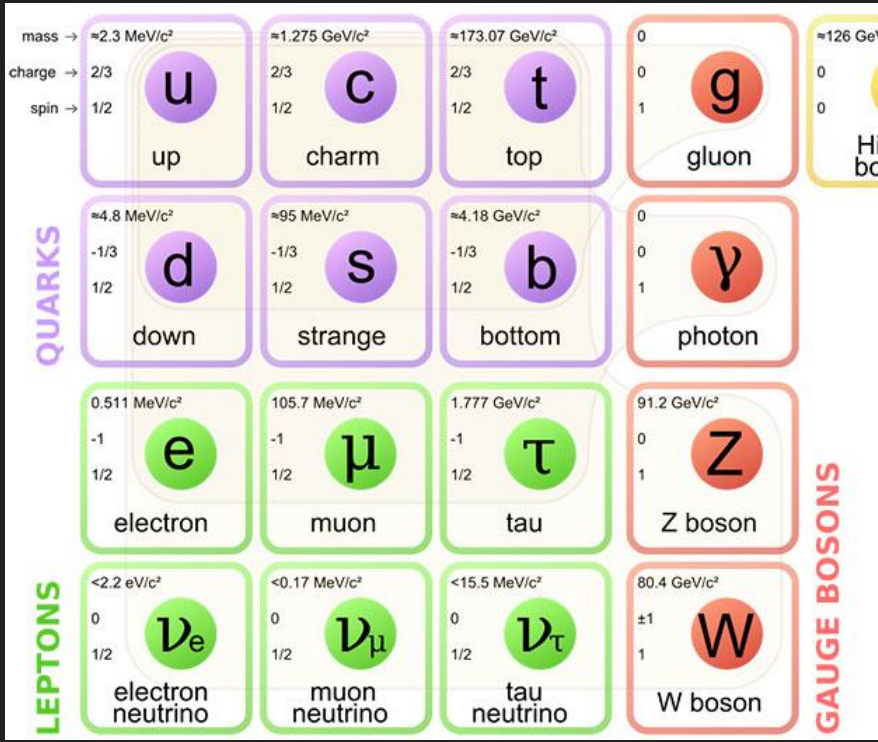
Along with Earth-based detectors, they can be probed using new observations in astrophysics/cosmology



https://www.abc.net.au/news/science/2017-07-15/the-standard-model-of-particle-physics-explained/7670338

Goal: Can we probe BSM self-interacting neutrino models (SINU) using the data from James Webb Space Telescope (JWST) observations?

What is Neutrino-self Interaction

$$\mathcal{L}_{eff} = G_{eff}(\bar{\nu}\nu)(\bar{\nu}\nu)$$

Effective Lagrangian

$$\Gamma_{\nu} = aG_{eff}^2 T_{\nu}^5$$

Interaction Rate

Standard Model: $G_{eff} = G_F \sim 10^{-11}\text{MeV}^{-2}$

BSM:

Moderately Interacting Neutrinos (MIν) :

$-2.5 \gtrsim \log_{10}(G_{eff}/MeV^{-2}) \gtrsim -5.5$

Strongly Interacting Neutrinos (SIν) :

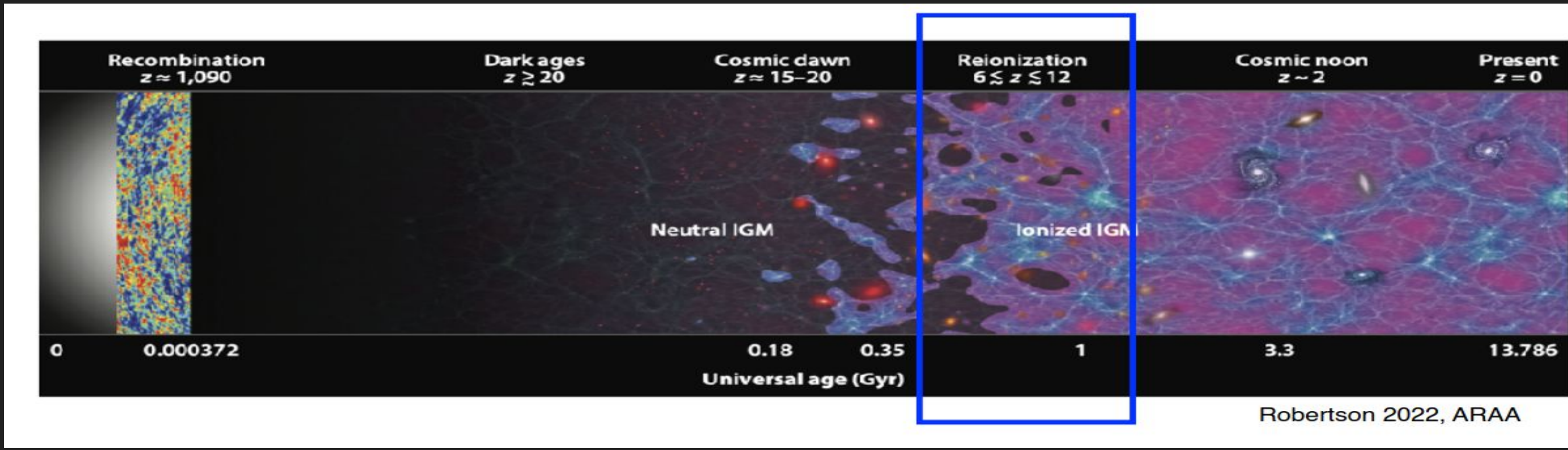
$-1 \gtrsim \log_{10}(G_{eff}/MeV^{-2}) \gtrsim -2.5$

a = Scale Factor

G_{eff} : effective coupling strength

T_{ν} = Neutrino Temperature

History of the Universe & Structure Formation



Recombination ⟶ Dark Ages ⟶ DM Overdensities collapse under their own gravity ⟶ Collapse of Gas ⟶ First Galaxies

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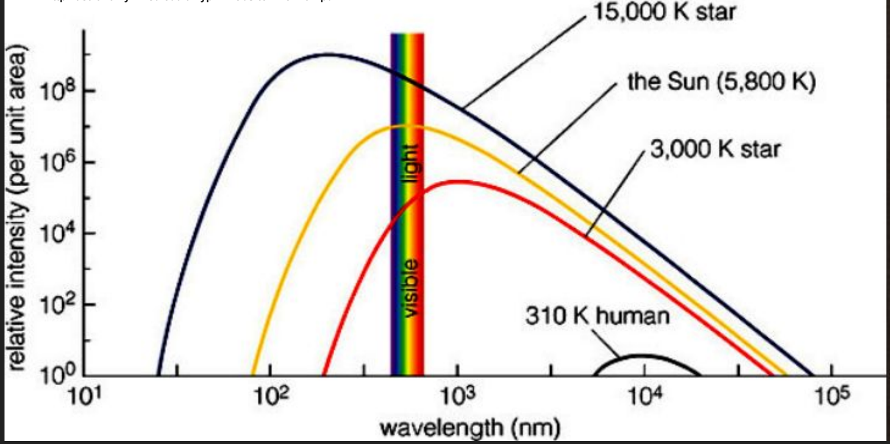
This region were not probed at all (before 2022).

Do we now have new data in this region?

Earliest Galaxies Observed

Young (thus hotter) stars emit in UV wavelengths

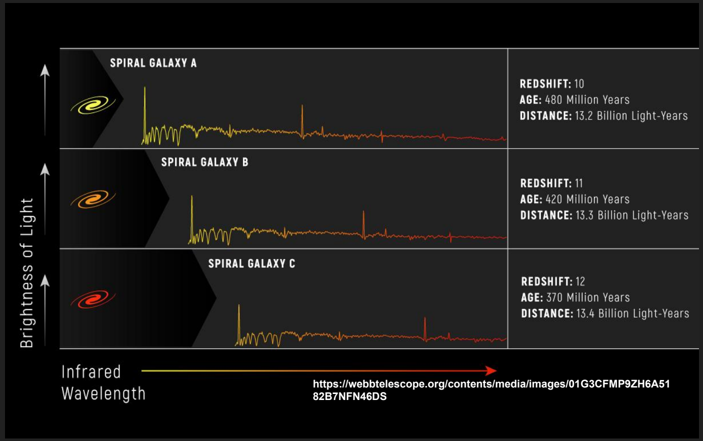
http://astronomy.nmsu.edu/aklypin/WebSite/Kirchhoff.pdf



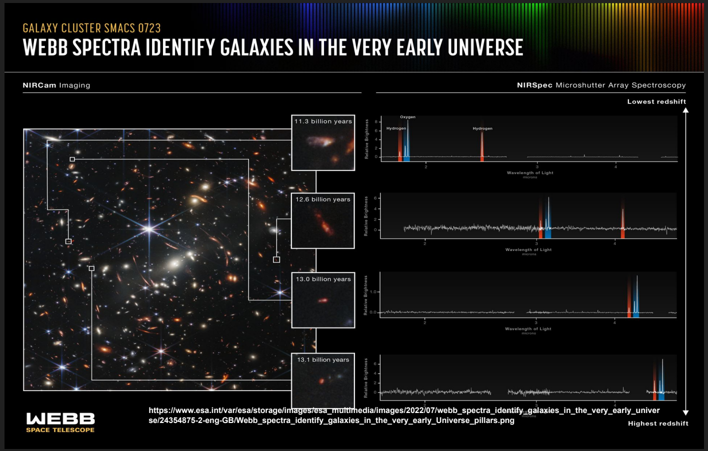
These UV emissions get redshifted to longer wavelengths (i.e., optical and IR)

$$\lambda_{obs} = (1 + z)\lambda_{emit}$$

We need more IR telescopes

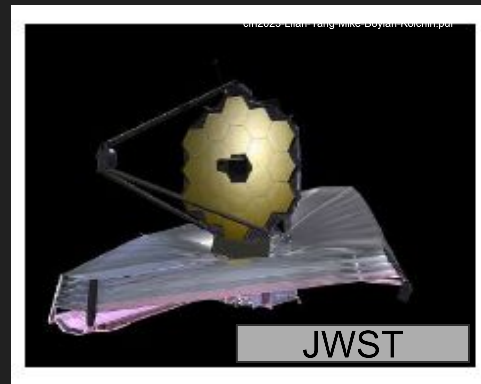


https://webbtelescope.org/contents/media/images/01G3CFMP9ZH6A5182B7NFN46DS



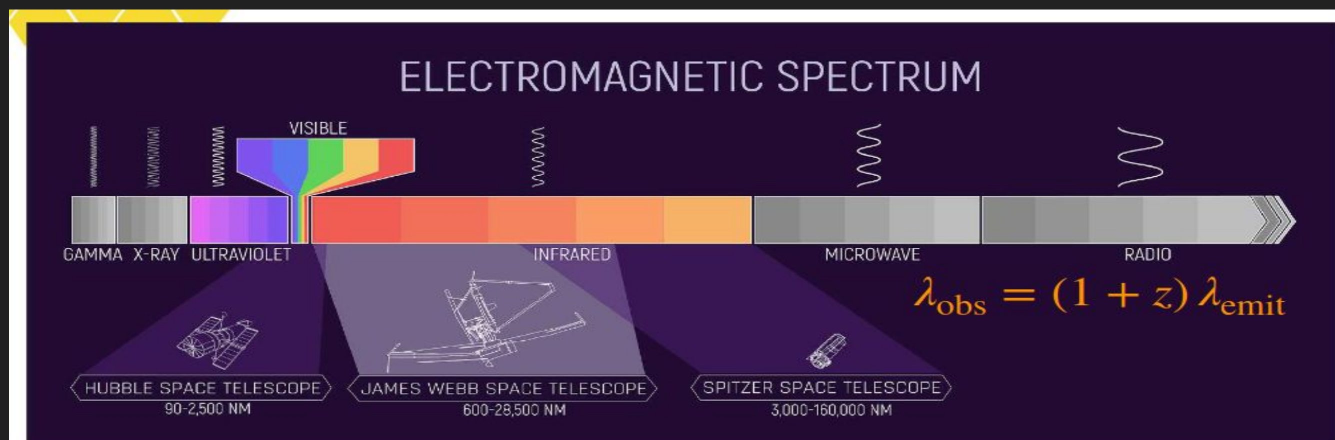
https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2022/07/webb_spectra_identify_galaxies_in_the_very_early_universe/24354875-2-eng-GB/Webb_spectra_identify_galaxies_in_the_very_early_Universe_pillars.png

JWST Observations



- **Where are the first stars/galaxies?**
- **Physics beyond standard ΛCDM (Λ-Cold dark matter) Model?**

JWST is observing infrared wavelengths at high redshifts (z ~ 8–14) using the following instruments onboard: NIRSpec, NIRCam, MIRI, and NIRISS

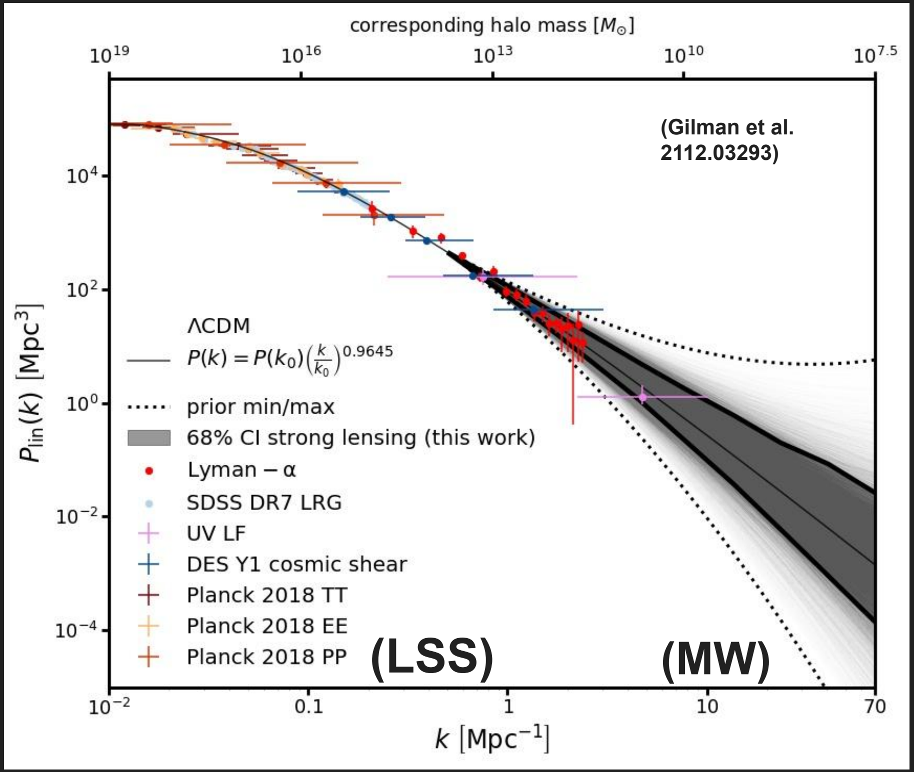


Three main questions to answer

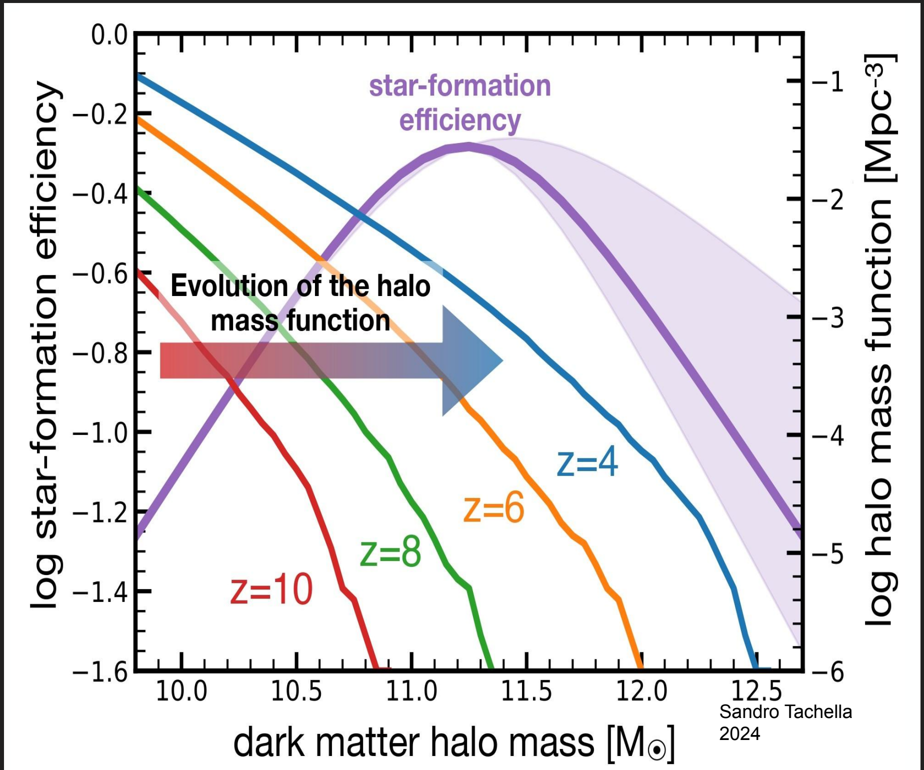
- What is JWST looking at?
- How does Self-interacting neutrinos affect structure formation?
- How do we probe neutrino self-interactions with JWST data?

What is JWST looking at?

A little Background Cosmology



Matter power spectrum (density contrast at a scale $\sim \frac{1}{k}$)



Halo mass function (Cosmology) and Star formation efficiency (Astrophysics)

What is UV Luminosity Function (UVLF)

UV Luminosity Function:

$$\Phi_{UV} = \frac{dn}{dM_{UV}} = \frac{dn/dM_h}{dM_{UV}/dM_h}$$

The number density of halo within unit brightness interval at a particular brighness

Halo Mass Function:

$$\frac{dn}{d\log M_h} = \frac{\rho_0}{M_h} f(\sigma) \left| \frac{d\log\sigma}{d\log M_h} \right|$$

Cosmology!

Dependence on P(k):

$$\sigma^2(R) = \frac{1}{2\pi^2} \int_0^\infty dk\, k^2 P(k) W^2(kR)$$

Dependence on Star formation rate:

$$\frac{dM_{UV}}{dM_h}$$

Astrophysics!!

Neutrino interactions will change the cosmology part only!!!

n : Number of galaxies per unit volume.

M_{UV} : Magnitude (Brightness)

M_h : Mass of a Halo.

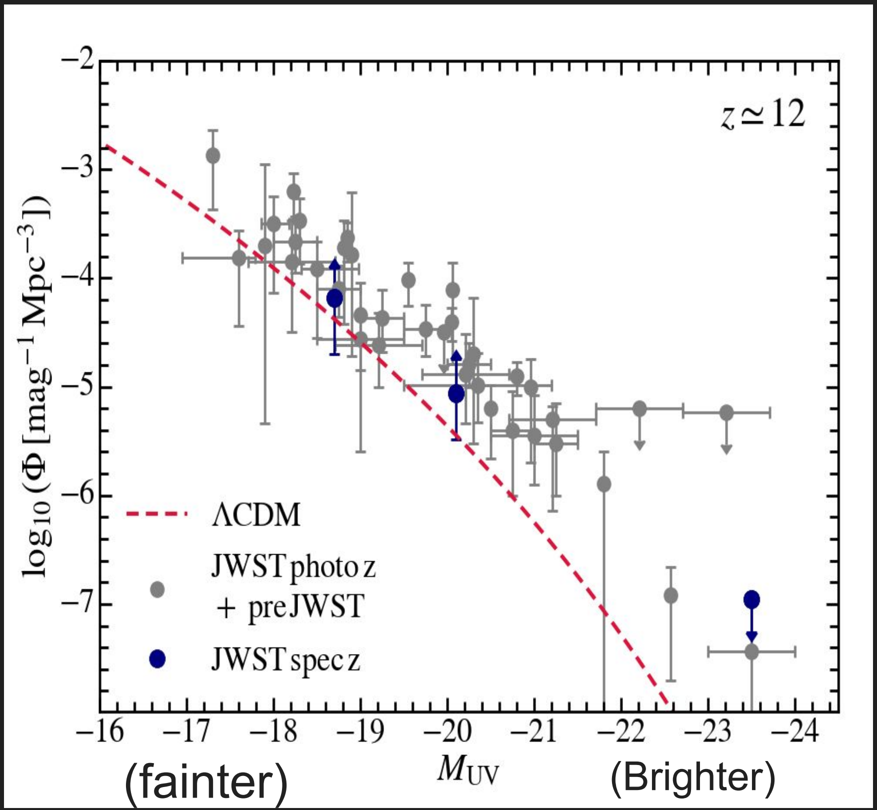
$\sigma(R)$: Smoothed mass variance as a function of scale (R).

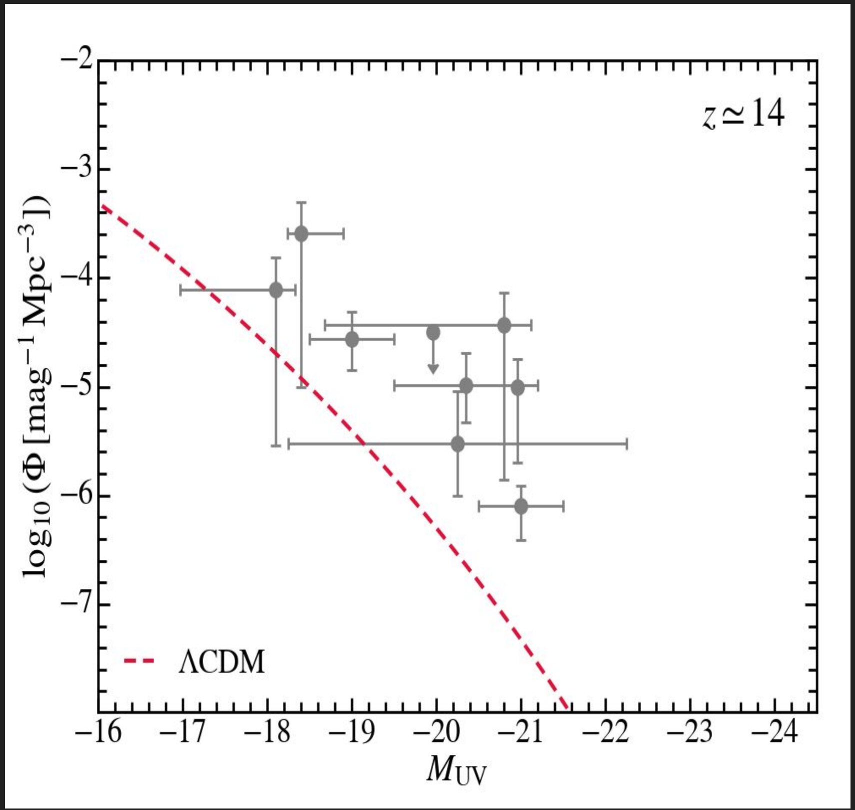
ρ_0 : Mean density of the universe at the present epoch

$f(\sigma)$: Seth-Tormen Fitting function (obtained from Press-Schechter formalism, corrected for ellipsoidal collapse)

What Has JWST Discovered?

(plots obtained by using https://github.com/XuejianShen/highz-empirical-variability.git)





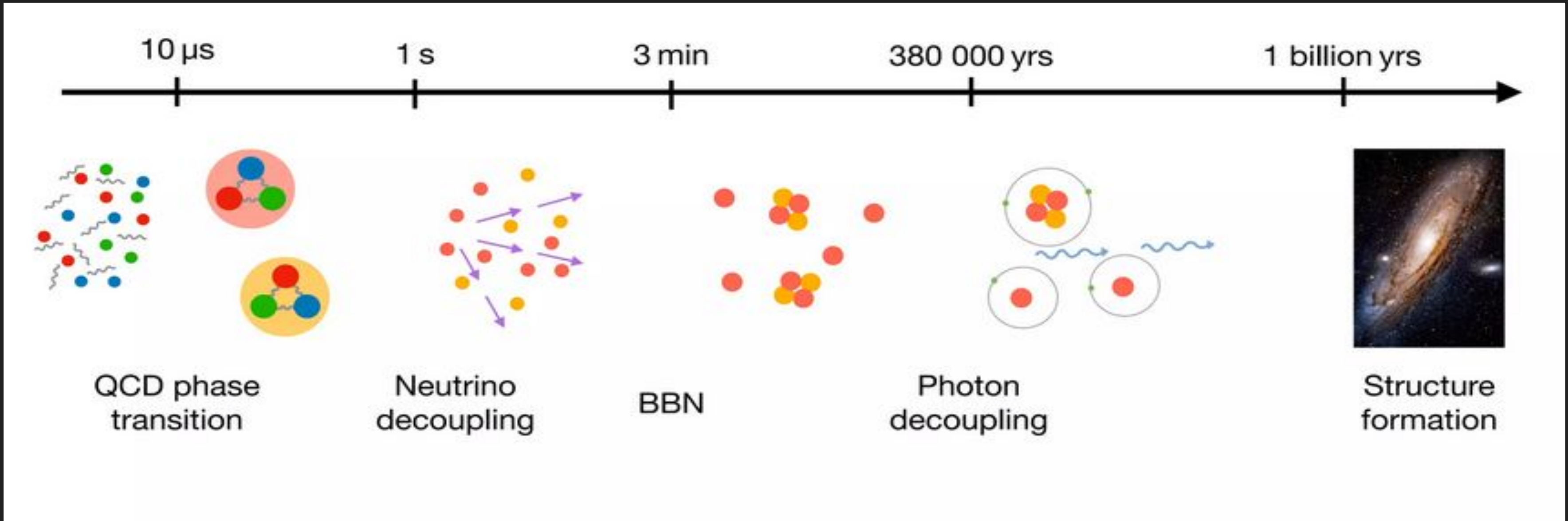
One can change the Astrophysics or Cosmology! →

We are studying the effect of change in cosmology through BSM neutrino self-interactions!

How does self-interacting neutrinos affect structure formation?

Neutrinos in the History of the Universe

Karl-Heinz-Spatscheck



Neutrino self interactions delay the free streaming of various neutrino species.

How does that affect the structure formation?

Effect of neutrino self-interactions in the early Universe

Anisotropic stress: $\sim \phi - \psi$

$$\phi = (1 + \frac{2R_\nu}{5})\psi$$

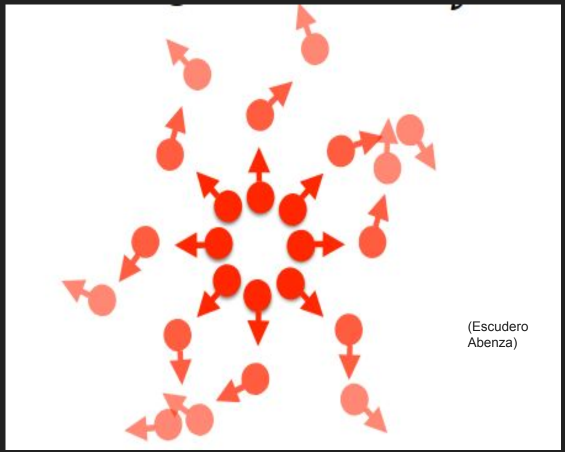
R_ν : Neutrino free streaming fraction

ϕ, ψ : Are metric perturbations in newtonian gauge

SINU Model

Neutrinos Interact → **Free Streaming Delayed** → **Anisotropic Stress zero**

(Unique characteristics in the matter power spectrum)



ΛCDM Model

Early free streaming

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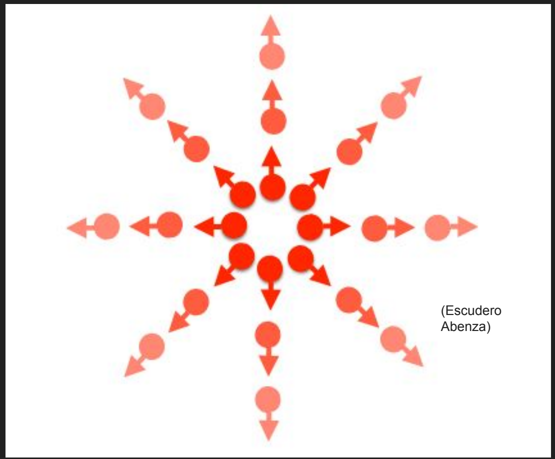
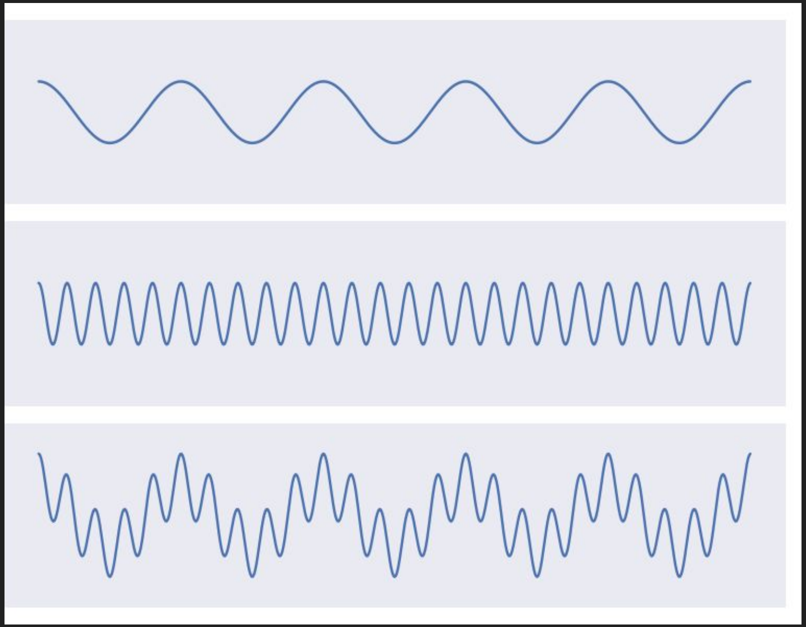
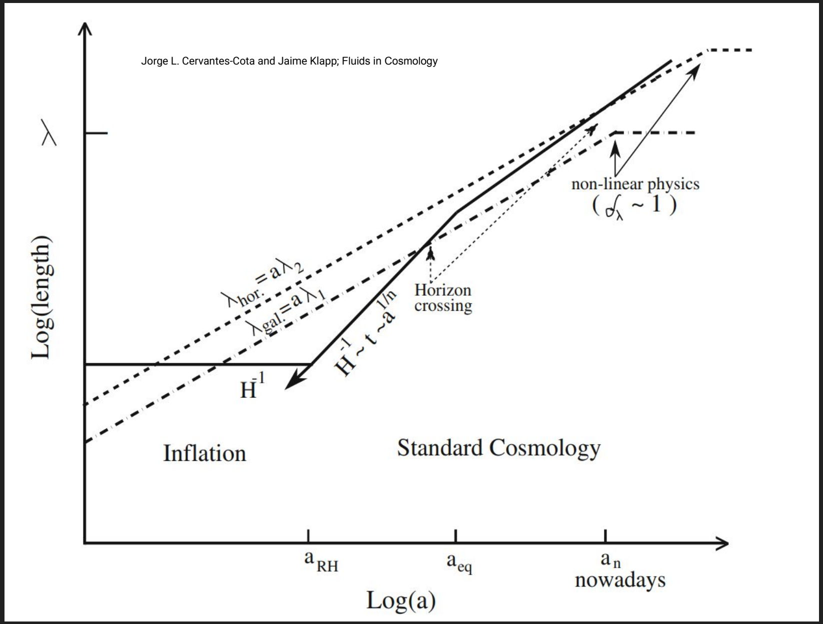
Non zero Anisotropic Stress



$\sim \phi - \psi$

Horizon entry and exit of different k modes





Dark matter overdensities can be decomposed into fourier modes

Different Fourier modes enter the horizon at different times (1/k ~ Horizon size)

- **Higher k (small scales) enter at earlier epochs and lower k (large scales) enter at later epochs.**
- **Some k Scale k_{fs} associated with neutrino free-streaming time!**

Changes in the power spectrum

k_{fs} : **Scale that enters the horizon during neutrino free streaming**

Neutrinos Interacting → Delayed Free Streaming

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Enhancement $(k \sim k_{fs})$, Suppression $(k > k_{fs})$

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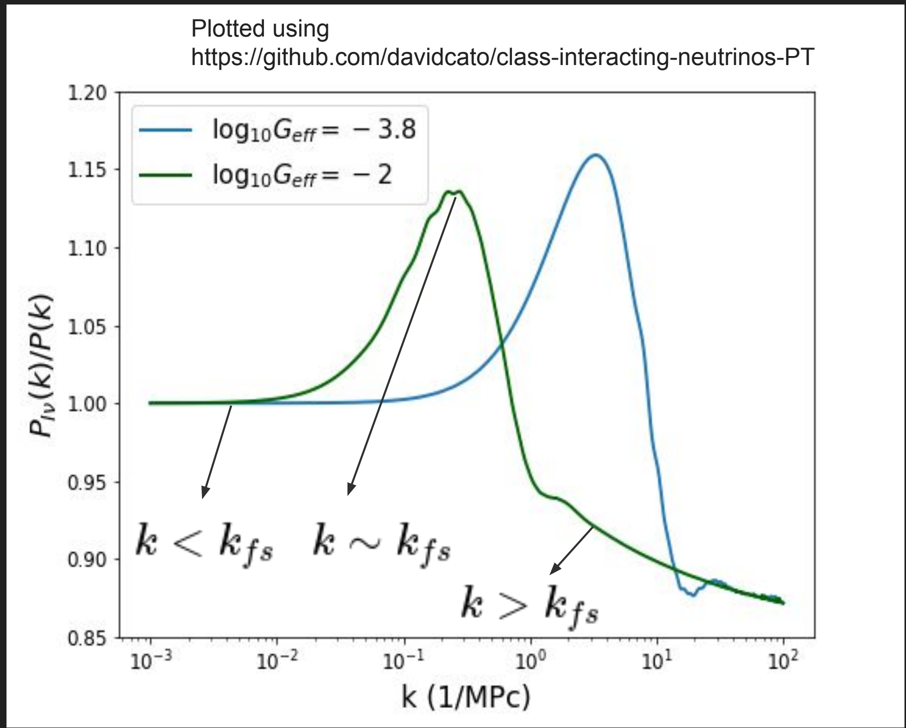
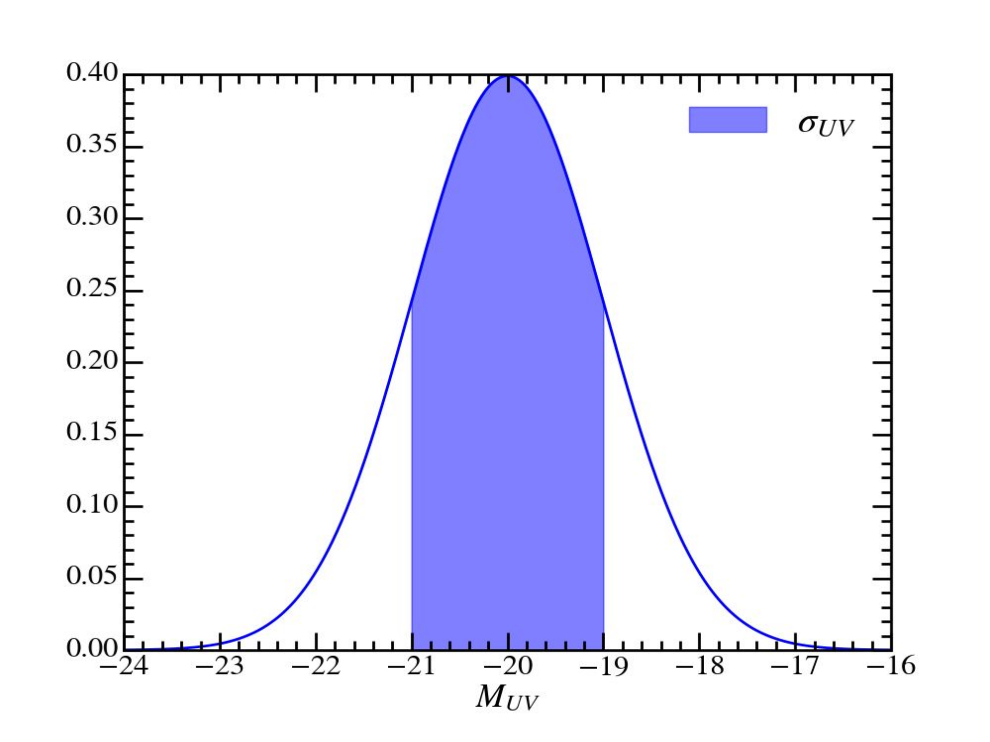
Can be probed by structure formation at small scales → JWST (Brighter Galaxies)



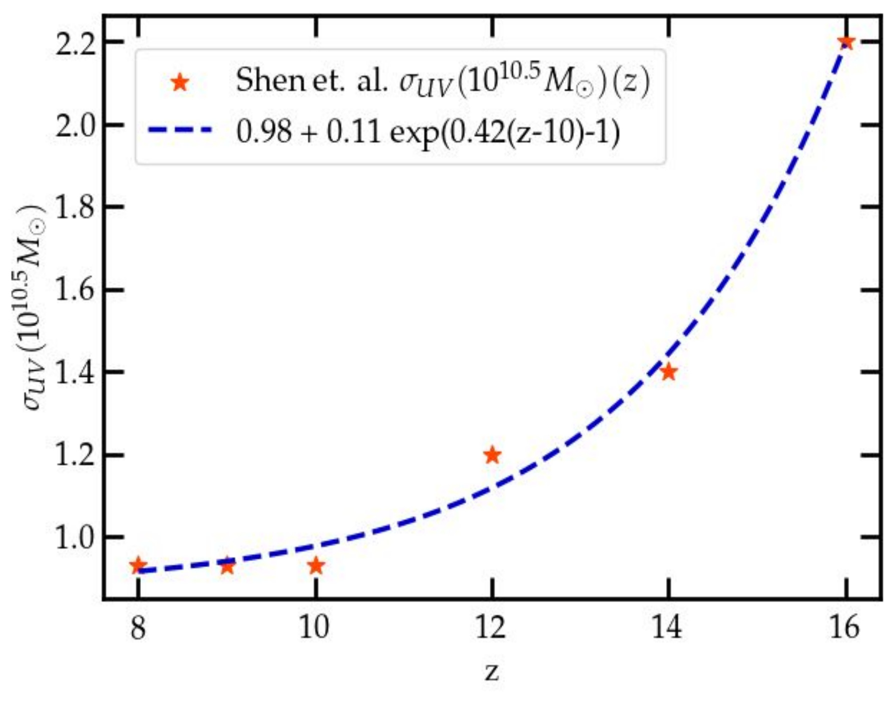
How do we probe the neutrino self-interactions with JWST data?

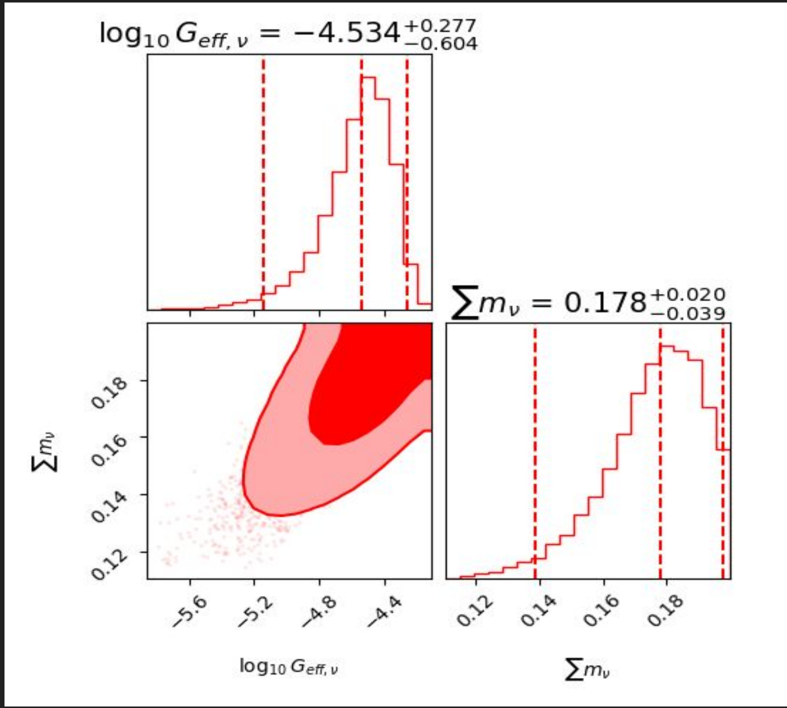
UV Variability



- A halo of mass M and at a redshift z, emits light of magnitude $\sigma_{UV}(M, z)$
- Smaller masses and emit brightly.
- Increases the UVLF

Halo Mass and Redshift-dependent Variability





M_h

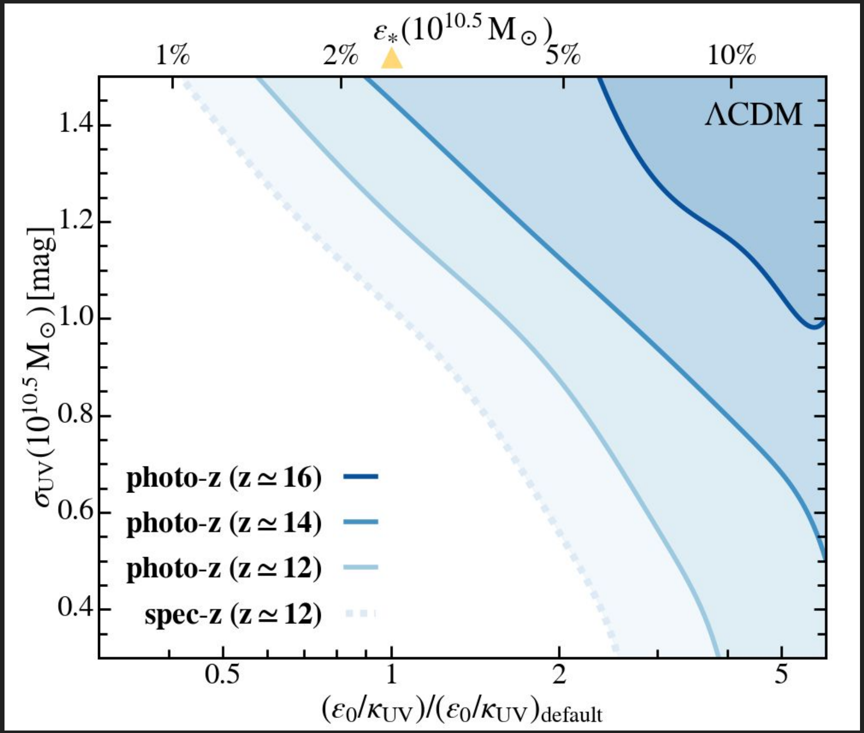
$$\sigma_{UV}(z, 10^{10.5}M_\odot) = 0.98 + 0.11(e^{0.42(z-10)} - 1)$$

$$\sigma_{UV}(z, M_h) = \sigma_{UV}(z, 10^{10.5}M_\odot) - 0.34\log_{10}\left(\frac{M_h}{10^{10.5}M_\odot}\right)$$

$\mathbf{M_h}$: Halo Mass

z : Redshift

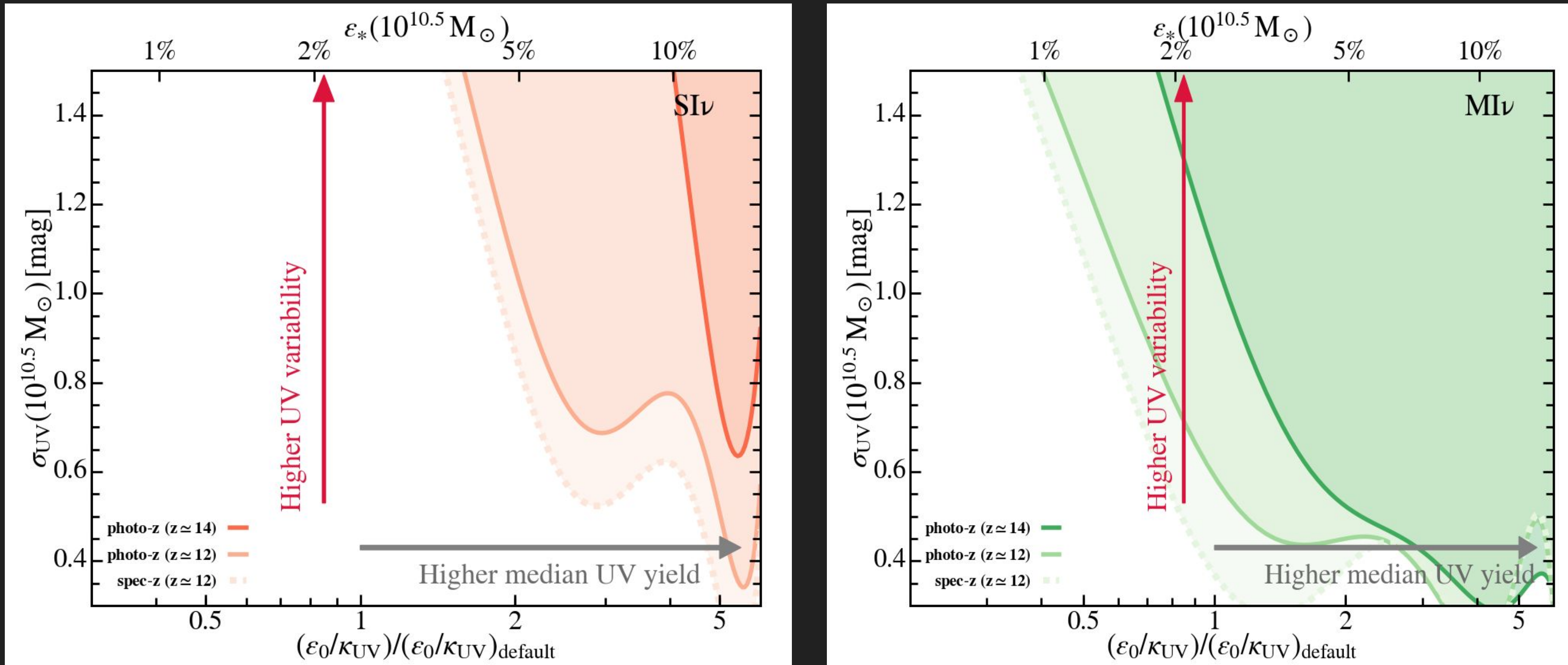
Parameter Space For LCDM



- Shaded regions ⟶ Astrophysical parameter space that can reproduce JWSTUVLF and Higher.
- Deeper the color ⟶ more challenging it is to reconcile the constraints

plotted by using https://github.com/XuejianShen/highz-empirical-variability.git
+ class-PT interacting neutrinos

Parameter constraints for self-Interacting neutrinos



MIν is more favoured as compared to SIν

Conclusions

- **JWST is observing young, massive galaxies at high redshifts.**

- **We can Probe BSM interactions using the data from the starlight of these early galaxies.**

- **In this work, we are probing BSM neutrino self interactions from these datasets.**