Bimodal/Schizophrenic neutrino as a bridge between inflation and dark energy

Chian-Shu Chen

National Center for Theoretical Sciences, Taiwan

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with Chia-Min Lin

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outline

- The idea
- The framework and schizophrenic neutrino
- Inflection point inflation and Dirac neutrino
- Growing neutrino and dark energy
- Conclusion

The idea : **seesaw mechanism !**

- Particle physics : SM neutrino masses are small because of right-handed neutrinos are heavy

Low scale physics <---> High energy physics

Light neutrino masses ~ sub-eV scale

GUT physics $M_N \sim \Lambda_{GUT}$

TeV physics : Higgs mechanism

- In cosmology, energy scale usually can be used to specify the evolution of the Universe

There are two epochs that the rate of increase of the scale factor accelerates : inflation and current expansion rate

- Inflation not only solves flatness problem, horizon problem, and unwanted relics from the big bang picture but also provides primordial density perturbations of baby Universe.
- Most inflationary models operate at energy scales of order 10^{15} GeV
- The observed accelerated expansion of the Universe could be due to a tiny Dark Energy $\rho^{1/4} \approx 2\times10^{-3}$ eV
- The coincidence that inflation ~ Λ_{GUT} and Dark Energy ~ m_ν
- Does inflation and dark energy have something to do with seesaw mechanism and neutrino physics that one might unify the two epochs in one framework.

→ The scheme we proposed in this work : if neutrinos are schizophrenic

The framework : **the neutrinos are schizophrenic !**

- MSSM⊗$U(1)_{B-L}$

  The anomaly B-L cancellation conditions can be satisfied by introducing three generations of right-handed neutrinos N^c

  The representations of the superfields are assigned as

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \sim (3, 2, 1/6, 1/3), \quad u^c \sim (3, 1, -2/3, -1/3), \quad d^c \sim (3, 1, 1/3, -1/3),$$

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \sim (1, 2, -1/2, -1), \quad e^c \sim (1, 1, 1, 1), \quad N_R \sim (1, 1, 0, 1),$$

$$H_u \sim (1, 2, 1/2, 0), \quad \text{and} \quad H_d \sim (1, 2, -1/2, 0).$$

- Note that $U(1)_{B-L}$ prohibits the right-handed neutrino Majorana mass

- We are not going to introduce new Higgs multiplets so that B-L symmetry is broken by the non-vanishing VEV of the right-handed sneutrino $\langle \tilde{N}_R \rangle$

- The neutrino mass matrix can be written as the form in the basis of

$(\nu_{Li}, N_{Ri}, \tilde{Z'}_{BL})$

$$m_\nu = \begin{pmatrix} 0_{3\times3} & m_D & -g_{BL}\langle\tilde{\nu}_L\rangle^T \\ m_D^T & 0_{3\times3} & M_{BL}^T \\ -g_{BL}\langle\tilde{\nu}_L\rangle & M_{BL} & M_{\rm SUSY} \end{pmatrix}$$

Note that there are three stages of symmetry breaking --

1. SUSY breaking ---> unknown (quintessence mediate)
2. Extra gauge $U(1)_{B-L}$ breaking ---> sneutrino VEVs
3. SM model gauge breaking ---> H_u and H_d

One can always rotate to the VEVs of right-handed sneutrinos to one direction, therefore the matrix elements

$M_{BL} = (0, 0, g_{BL}\langle\tilde{N}_{R3}\rangle)$ and $m_D = Y_\nu\langle H_u\rangle$

We will neglect the contributions of left-handed sneutrino VEVs, which mix the left-handed neutrinos with neutrilinos and are bounded $\langle\tilde{\nu}_L\rangle$ < 1 MeV if M_{SUSY} < 1 TeV.

- The lower right 2×2 block matrix reads

$$M_{N_{R3},\tilde{Z}'_{BL}} = \begin{pmatrix} 0 & g_{BL}\langle \tilde{N}_{R3} \rangle \\ g_{BL}\langle \tilde{N}_{R3} \rangle & M_{\rm SUSY} \end{pmatrix}$$

It is not surprise that we have Majorana masses of neutrinos after B-L symmetry breaking, the rest 5×5 mass matrix is given by

$$M_{\rm light} = \begin{pmatrix} m_{\nu_1} & 0 & 0 & m_D^1 & m_D^2 \\ 0 & m_{\nu_2} & 0 & m_D^3 & m_D^4 \\ 0 & 0 & 0 & m_D^5 & m_D^6 \\ m_D^1 & m_D^3 & m_D^5 & 0 & 0 \\ m_D^2 & m_D^4 & m_D^6 & 0 & 0 \end{pmatrix},$$

Finally these models generally predict three layers of neutrinos: one heavy sterile neutrino, two massive active neutrinos, and three nearly "massless" (one active and two sterile) neutrinos.

Three active masses $m_{\nu_{1,2}} \simeq Y_{\nu_{1,2}} v_u$ and $m_{\nu_3} \simeq \frac{Y_{\nu_3}^2 v_u^2}{M_{R3}}$

- The effective Yukawa interactions of active neutrino masses ca be written as

$$L_\nu = Y_{\nu_1} L_1 H_u N_{R1} + Y_{\nu_2} L_2 H_u N_{R2} + \frac{Y_{\nu_3}^2}{M_{R3}} (L_3 H_u)^2 + \text{H.c.}.$$

Remarks for the extra two light sterile neutrinos

1. The two lights states may be welcome in view of the oscillation anomalies in LSND, MiniBooNE, and MINOS.

2. The recent observations from CMB anisotropies and the large-scale structure (LSS) distribution indicate the allowance of extra radiation --- WMAP ($N_{eff} = 4.34^{+0.86}_{-0.88}$) and SDSS ($N_{eff} = 4.78^{+1.86}_{-1.79}$).

Inflection point inflation : **SUSY flat direction**

- Many inflation models treat the inflaton as a SM gauge singlet and sometimes their origin and coupling are chosen ad hoc just to fit the observed cosmological data.

- In any model, the inflation potential must be very flat, which is suggested of either a symmetry or a small coupling.

- A SUSY flat direction, which are classified by gauge invariant combinations of superfields, having a vanishing potential in the limit of an exact supersymmetry ------- Various contributions such as soft SUSY breaking terms lift the flatness of the potential.

- In our framework, the combination of superpartners $\phi = \frac{\tilde{N}_R + H_u + \tilde{L}}{\sqrt{3}}$ is a D-flat directions under the whole gauge symmetry, and is also F-flat when neutrino Yukawa coupling Y_ν are turned off.

- Let’s consider the flat direction $\phi = \frac{\tilde{N}_R + H_u + \tilde{L}}{\sqrt{3}}$ and include the soft SUSY breaking terms, such as the mass terms and the A-term (Affleck-Dine baryogenesis)

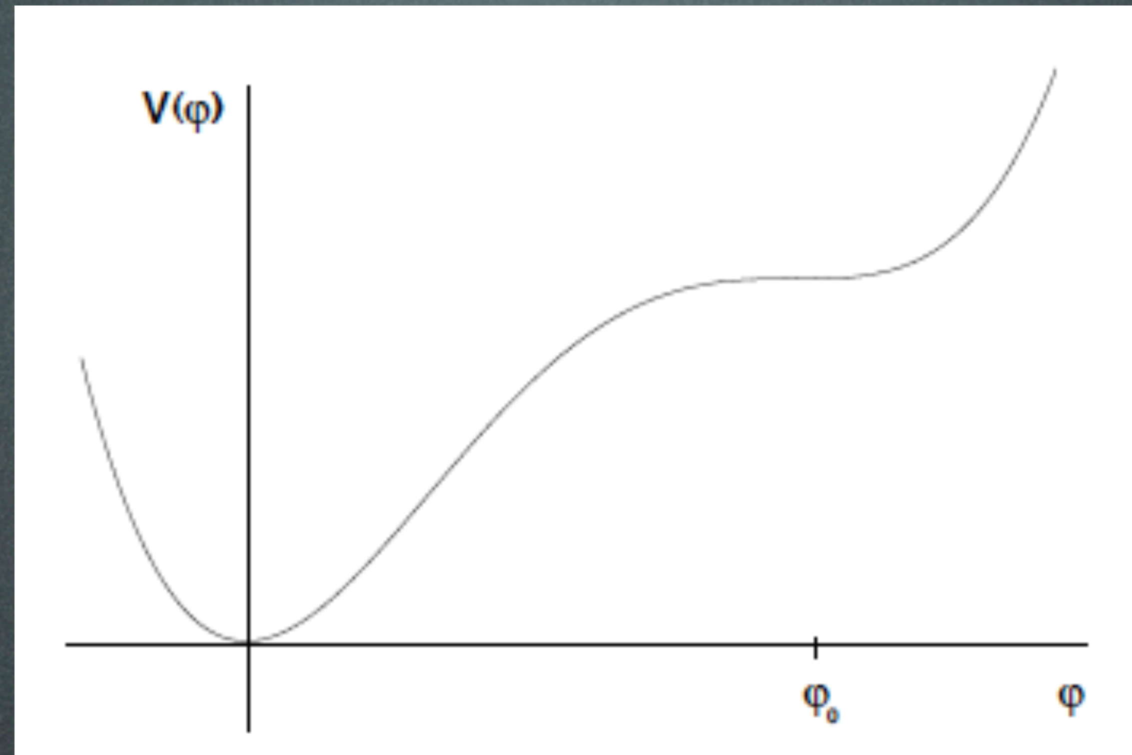
- The potential along the flat direction is given by

$$V(\phi) = \frac{1}{2}m^2\phi^2 - AW + \left|\frac{\partial W}{\partial \phi}\right|^2 = \frac{1}{2}m^2\phi^2 - \frac{Ah}{6\sqrt{3}}\phi^3 + \frac{h^2}{12}\phi^4,$$

with $W = \frac{\lambda_n}{n}\frac{\Phi^n}{M_{\rm P}^{n-3}}$,

the minus sign comes from the phases of the Yukaw coupling h and the A-term $\cos(\theta + \theta_h + \theta_A)$

The potential is minimized when $\cos(\theta+\theta_h+\theta_A) = -1$. Along this direction $V(\phi)$ has the global minimum at $\phi = 0$ and a local minimum at $\phi_0 \sim m_\phi/h$, as long as $4m_\phi \leq A \leq 3\sqrt{2}m_\phi$



- If $A > 3\sqrt{2}m_\phi$, the minimum at ϕ_0 will become global.

$V''' = 2hm/\sqrt{3}.$

- A = $4m_\phi$ is assumed in order to obtain a saddle point $\phi = \phi_0 = \sqrt{3}m/h$ where we have

One can expand the potential near the saddle point

$$V(\phi) = V(\phi_0) + (1/3!)V'''(\phi_0)(\phi - \phi_0)^3 \qquad V''' = 2hm/\sqrt{3}$$

- Having the potential, one can follow the standard procedure

slow roll parameter $$|\eta| \equiv |\frac{V''}{V}| = 2\left(\frac{2h}{m}\right)^2 |\frac{(\phi-\phi_0)}{\phi_0}| \sim 1$$

the number of e-folds $$N = \int_{\phi_{end}}^{\phi} \frac{V}{V'} d\phi \sim \left(\frac{m}{2h}\right)^2 \frac{\phi_0}{(\phi_0-\phi)}$$

Therefore, we have $\eta \sim -2/N$. This implies the spectral index is given by $n_s \sim 1 + 2\eta = 1 - 4/N$

- For the scale of CMB, N =50, we have $n_s = 0.92$.

- The constraint for the parameter m_ϕ and h is from the CMB temperature fluctuation. The spectrum is given by

$$P_\zeta = \frac{1}{12\pi^2}\left(\frac{V}{V'}\right)^2 V = \frac{h^4}{9\pi^2 m^2} N^4$$

$$P_\zeta^{1/2} = \frac{h^2}{3\pi m} N^2 = 5\times 10^{-5}$$ (for $\Delta T/T \sim 10^{-5}$) ⟶ m ~ TeV we need $h \sim 10^{-12}$

Dark energy : **the neutrino mass is growing !**

- The origin of dark energy is unknown, be it a cosmological constant, a dynamical dark energy due to a scalar field (quintessence), a modification of gravity, or something still unexpected.
- A pressing question arises: why has the cosmological acceleration set in only in the rather recent cosmological past ? Transition from the matter dominated Universe to a scalar field dominated Universe at redshift $z \cong 0.5$
- A similar crossover from radiation to matter domination occurred in earlier Universe since the dilution of the energy density with scale factor a obeys $\varrho_\gamma \propto a^{-4}$ for radiation and $\varrho_m \propto a^{-3}$ for matter.
- The scheme of growing matter suggests the presently observed crossover to a dark energy dominated Universe is of a similar type.
- "Growing matter" is an unusual form of matter whose mass increases with time and hence its energy density decreases slower than the one of the usual cold dark matter.

- "growing neutrinos" yields interesting relation between the present mass of the neutrinos and the dark energy density.
- Majorana component of schizophrenic neutrinos $\frac{Y_{\nu_3}^2}{M_{R3}}(L_3 H_u)^2$

If the mass of right-handed neutrino is decreasing, $m_{\nu 3}$ is increasing

- Remember : the 2×2 block mass matrix of N_{R3} and $\tilde{Z}'_{BL}$

$$M_{N_{R3},\tilde{Z}'_{BL}} = \begin{pmatrix} 0 & g_{BL}\langle \tilde{N}_{R3} \rangle \\ g_{BL}\langle \tilde{N}_{R3} \rangle & M_{\mathrm{SUSY}} \end{pmatrix}$$

Consider the superpotential $W = \Lambda^{3+\gamma} Q^{-\gamma}$ and a Kahler potential $K = -\ln(Q+Q)$

P. Brax and J. Martin (1999,2000); E.J. Copeland, N.J. Nunes, and F. Rosati (2000)

This kind of form is present for the dilaton and moduli fields in string theory

- The scalar potential in supergravity is given by

$$\begin{aligned} V &= e^K[(W_i + WK_i)K^{j^*i}(W_j + WK_j)^* - 3|W|^2] \\ &= M^4 e^{-\alpha\chi} \end{aligned}$$

here χ is the canonically normalized field defined by $\chi \equiv \ln Q/\sqrt{2}$

and $M^4 = \Lambda^{5+\kappa}(\kappa^2 - 3)/2$ with $\kappa \equiv 2\gamma + 1$ and $\alpha \equiv \sqrt{2}\kappa$

- We assume the soft mass M_{SUSY} of $\tilde{Z'}_{BL}$ is determined by the expectation value of Q. In terms of χ, we have $M_{\rm SUSY} = \overline{M} Q^{-\epsilon/\sqrt{2}}$

so $M_{N_{R3}} \sim M_{BL}\left[1 - \frac{1}{\tau}\exp(-\epsilon\chi)\right]$

- χ is the quintessence field (cosmon) and the scaling solution means the fraction of dark energy is a constant depends on α

$\Omega_h = \frac{n}{\alpha^2}$ with n=3(4) for matter(radiation) dominant epoch

$$M_{N_{R3}} \sim M_{BL} \left[1 - \frac{1}{\tau} \exp(-\epsilon\chi)\right]$$

here $\tau = M_{BL}/\overline{M}$ and $\chi_t = -\ln\tau/\epsilon$ is defined as $M_{N_{R3}}(\chi_t) = 0$.

So the neutrino mass through seesaw mechanism providing

$$m_\nu = \overline{m}_\nu \{1 - \exp[-\epsilon(\chi - \chi_t)]\}^{-1}$$ with $$\overline{m}_\nu = \frac{Y_{\nu 3}^2 v_u^2}{M_{BL}}$$

For $\varepsilon < 0$, the neutrino mass increases when χ approaches χ_t

The equation of motion of cosmon field χ (quintessence) is

$$\ddot{\chi} + 3H\dot{\chi} = \frac{\partial V}{\partial \chi} + \beta(\chi)(\rho_\nu - 3p_\nu),$$
$$\beta(\chi) = -\frac{\partial}{\partial \chi} \ln m_\nu(\chi) = \frac{1}{\chi - \chi_t}$$

Here ρ_ν and p_ν are the neutrino energy density and pressure, obeying

$$\dot{\rho} + 3H(\rho_\nu + p_\nu) = -\frac{\dot{\chi}}{\chi - \chi_t}(\rho_\nu - 3p_\nu).$$

For χ near χ_t we have $$m_\nu(\chi) = \frac{\beta(\chi)}{\epsilon}\overline{m_\nu}.$$

The equations mean the energy exchange between neutrinos and the cosmon due to the varying neutrino mass

The effective coupling β is divergent for $\chi \to \chi_t$, and this effects stops the evolution of χ. As a consequence, the potential energy approaches a constant $V(\chi) \to V(\chi_t)$, which acts similar to a cosmological constant and causes the accelerated expansion.

$$\begin{aligned} V &= e^K[(W_i + WK_i)K^{j^*i}(W_j + WK_j)^* - 3|W|^2] \\ &= M^4 e^{-\alpha\chi} \end{aligned}$$

- For $M \sim M_P$, $\alpha\chi_t \sim 276$ and the upper bounds on early dark energy from $\Omega_h = \frac{n}{\alpha^2}$ require $\alpha > 10$.

We choose $\alpha = 10$ and $\chi_t = 27.6$ → $\ln \tau = \mathcal{O}(1)$ and $\epsilon \sim -0.05$

This means a rather mild χ-dependence of the soft mass $M_{\rm SUSY} = \overline{M} Q^{-\epsilon/\sqrt{2}}$

- For a given α and τ a different value for ε would change $\alpha\chi_t$ and therefore the present dark energy density.

⟶ This would change the time of trigger event

$$m_\nu(\chi) = \frac{\beta(\chi)}{\epsilon}\overline{m_\nu}.$$

Let's define the dimensionless variables

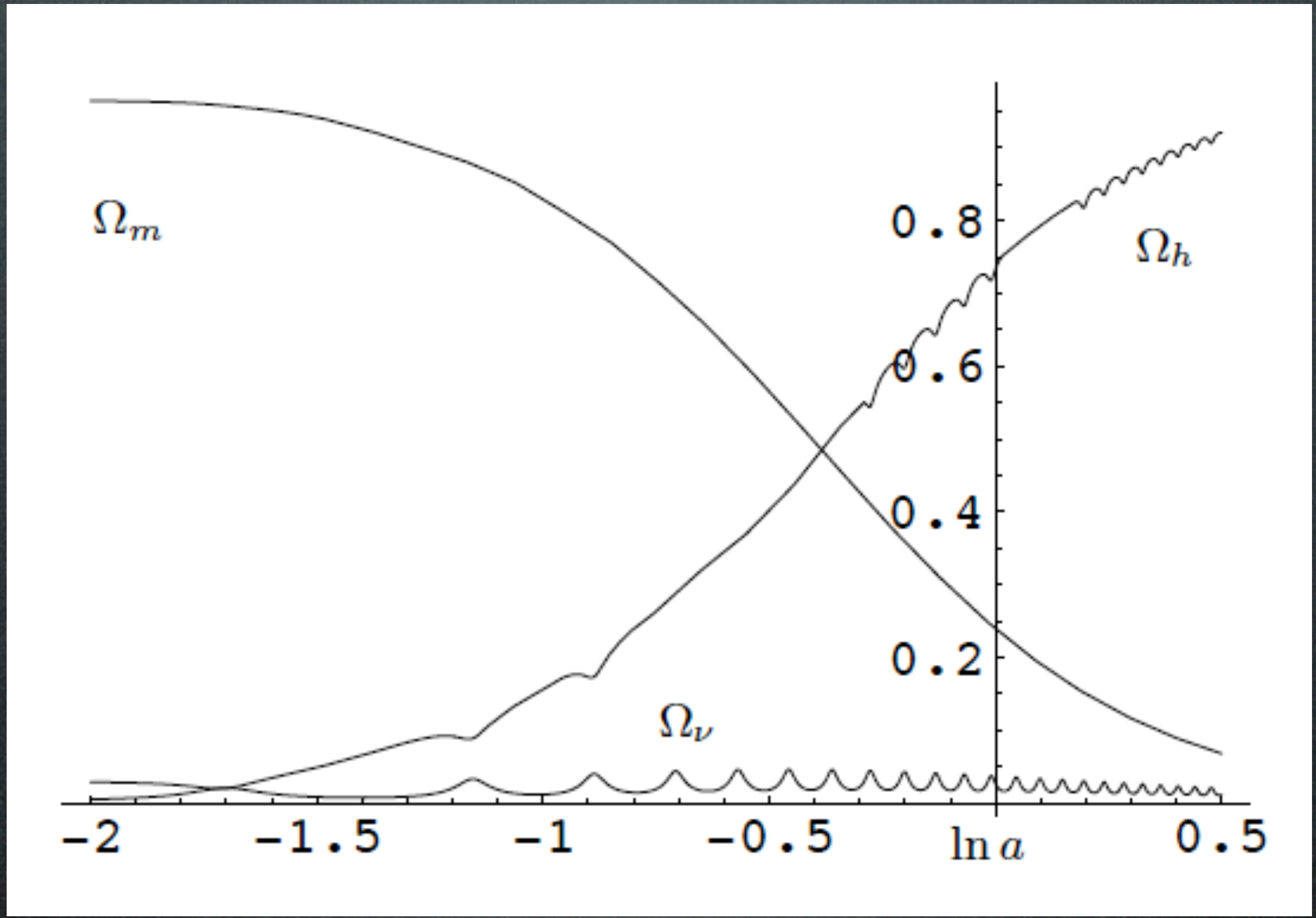
$s = -\alpha(\varphi - \varphi_t)/M$ $x = \ln a$ $\partial_t = H\partial_x$ with $V = V_t e^s$

The field equations for a homogeneous and isotropic universe can be cast into the form of evolution equations for the energy density of matter ρ_m (cold dark matter and baryons), radiation ρ_γ, neutrinos ρ_ν, and the cosmon

$$\rho_h = V + M^2\dot{s}^2/2\alpha^2$$

$$\begin{aligned}
\partial_x \ln \rho_m &= -3\ ,\ \partial_x \ln \rho_\gamma = -4, \\
\partial_x \ln \rho_\nu &= -3(1+w_\nu) + \frac{\beta(s)}{\alpha}(1-3w_\nu)\partial_x s, \\
\partial_x \ln \rho_h &= -6\left(1 - \frac{V}{\rho_h}\right) - \frac{\beta(s)}{\alpha}(1-3w_\nu)\frac{\rho_\nu}{\rho_h}\partial_x s, \\
\partial_x s &= \partial_x \ln V = -\sqrt{\frac{6\alpha^2(\rho_h - V)}{\rho_h + \rho_\nu + \rho_m + \rho_\gamma}}.
\end{aligned}$$

- Assuming flat universe $\rho_h + \rho_\nu + \rho_m + \rho_\gamma = 3M^2H^2$



C. Wetterich (2007)

with $\alpha = 10, \bar{m}_\nu = 7 \cdot 10^{-5} eV, \varphi_t/M = 27.648, \epsilon = -0.05.$

Conclusion and remarks

- We provide a schizophrenic neutrino scheme to connect inflation and dark energy
- The flat directions from supersymmetric scenario are the good candidate for inflation - there is no singlet field (with ad hoc mass and coupling) involved in order to explain inflation.
- Growing neutrino provides interesting framework to dark energy explanation.
- $MSSM \otimes U(1)_{B-L}$ has rich collider phenomenologies along the angle of R-parity conserved or violated cases.
- Schizophrenic neutrino has interesting implications for neutrinoless double beta decay.
- Neutrino cluster in the structure formation.

Thank you !