Title: Dark Energy and Neutrino Oscillations

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Abstract: In this talk I provide a model where the late time acceleration of the universe emerges from a BCS-like condensation of sterile neutrinos. This scenario can be naturally accommodated by general relativity covariantly coupled to sterile neutrinos, where the neutrinos act like an "aether" field. We show that when active neutrinos couple to the neutrino condensate, they oscillate at a rate proportional to the dark energy density. As a result, the oscillation of neutrinos and dark energy are tied in with the same mechanism. I also show that neutrinos could oscillate even if dark energy is not a neutrino condensate. I end with a discussion of stability of this model and predictions of CPT violating oscillations of such models.

Dark Energy and Neutrino Oscillations

Stephon H.S. Alexander

Dartmouth College
&
Princeton University

S.A 2008, S.A, A. Marciano, D. Spergel to appear

PI Cosmology Seminar

Philosophy

- Most Dark Energy Models based on two assumptions:
- Introduce New Degrees of Freedom
- Introduce New Physics

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- Most Dark Energy Models based on two assumptions:
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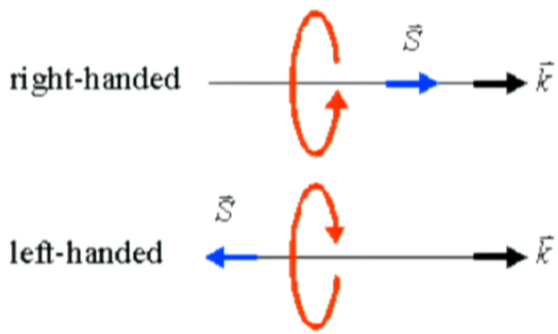
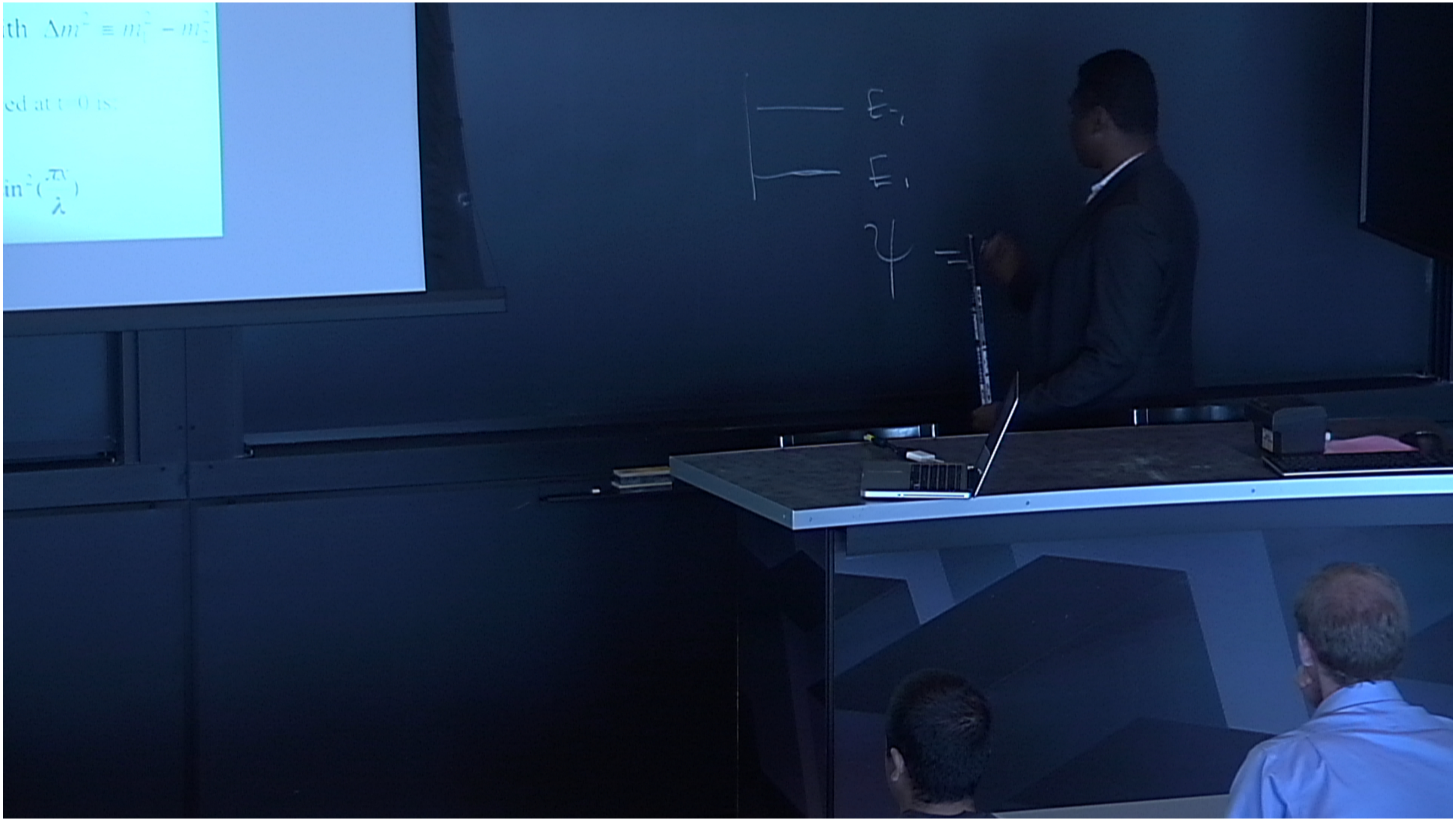
- I Present two models of dark energy where new degrees of freedom are introduced.
- However, the physics is known.

Both Models Naturally Accomodate Neutrino Oscillations

Neutrinos in the Standard Model

- Electromagnetically neutral leptons
- Handedness (chirality): no right-handed neutrinos
- Higgs field => neutrinos are massless
- Interact only via the weak interaction




ith
ed at t=0 is:
E_2
E_1
$\psi =$

$\Delta m^2 = 2.2\text{x}10^{-3}$ eV^2 assume $<E_\nu>=10^3$ MeV

$\lambda_{osc} = (\pi/1.27)(<E_\nu>/\Delta m^2) = (\pi/1.27)(10^3/2.2\text{x}10^{-3}) = 1.1\text{x}10^6$ m (≅620miles)

Lets pay attention to Δm^2

For the lepton couplings to the W boson, we then have —

$$|\nu_l\rangle = \sum_{l,m} U_{l,m} |\nu_m\rangle$$

Left-handed

W-boson

$$L_{SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \left(\bar{\ell}_{L\alpha}\gamma^\lambda \nu_{L\alpha} W_\lambda^{\ -} + \bar{\nu}_{L\alpha}\gamma^\lambda \ell_{L\alpha} W_\lambda^{\ +} \right)$$

$$= -\frac{g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \left(\bar{\ell}_{L\alpha}\gamma^\lambda U_{\alpha i} \nu_{Li} W_\lambda^{\ -} + \bar{\nu}_{Li}\gamma^\lambda U_{\alpha i}^{\ *} \ell_{L\alpha} W_\lambda^{\ +} \right)$$

Taking mixing into account

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Taking mixing into account

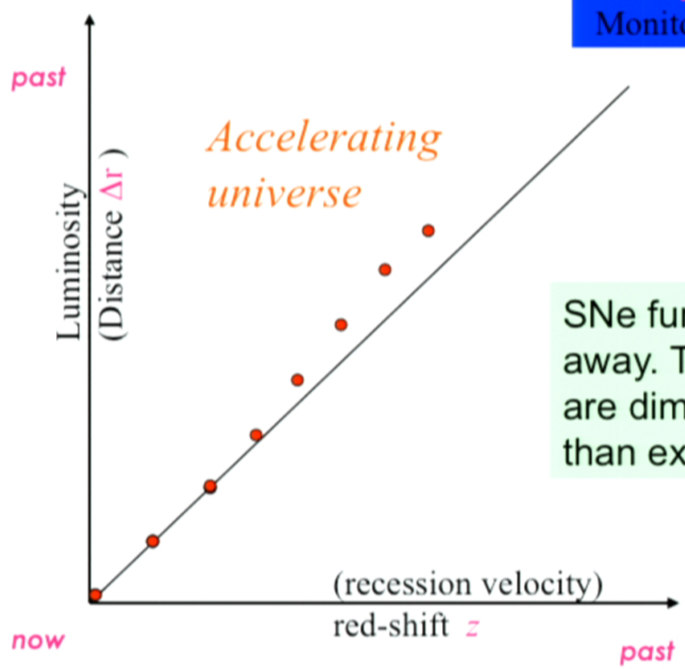
Hubble curve bends upward !

Surprising discovery

To see the bending of the *Hubble curve*, need to measure objects across enormous distances. Just such 'standard candles' have been found:

Type-1a Supernovae

Monitoring thousands of galaxies → SN/(month)



SNe further away. They are dimmer than expected

Involves catching the light of exploding stars **emitted billions of years ago**

… and their intrinsic luminosity understood

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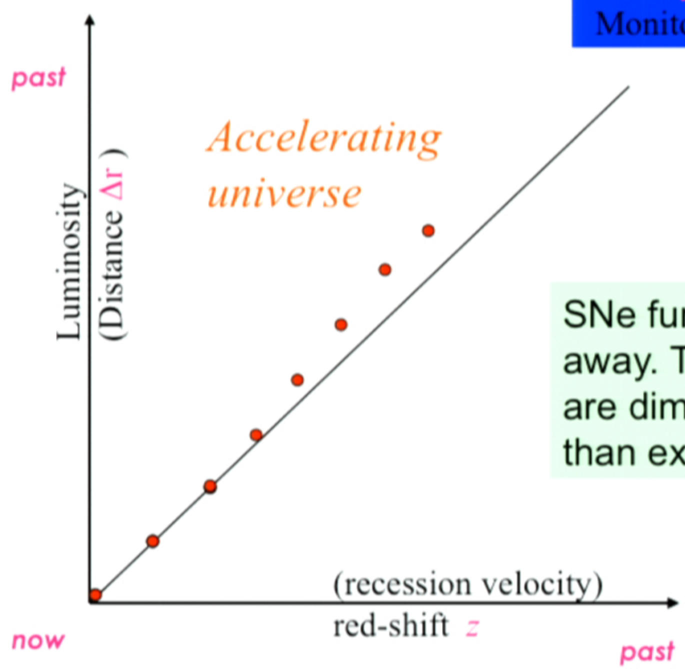

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Coincidence?

$$\Delta^2_{atm} \simeq 10^{-3} eV^2$$

$$\rho_{DE} \simeq (10^{-3} eV)^4$$

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There are lot's of
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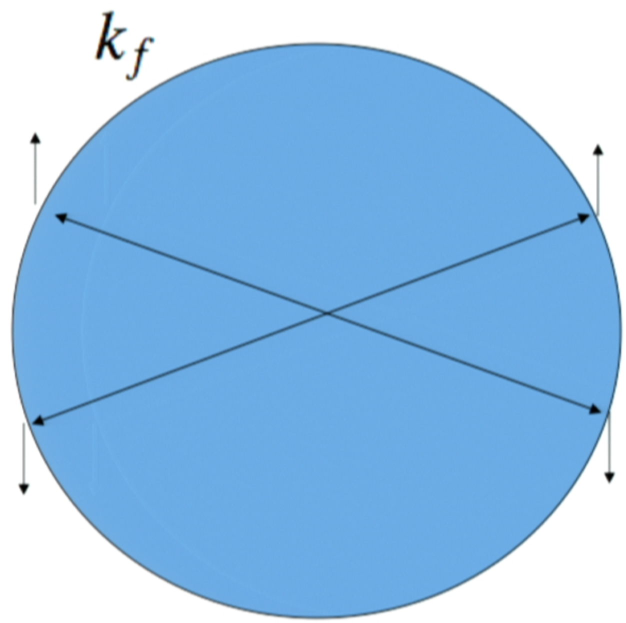
Model I: Sterile Neutino Condensate (S.A 2007)

- Gravitational Effects cause Neutrino's to form a homogenous BCS-like condensate.
- Condensate Leads to generic late time acceleration (Dark Energy)
- When neutrinos propagate in its condensate medium they experience "mass" oscillations proportional to DE density.
- Potential conncetion to CMB physics.

BCS Theory: Fundamentals

Key: Correlations of fermions across Fermi surface



General Relativity and Neutrinos

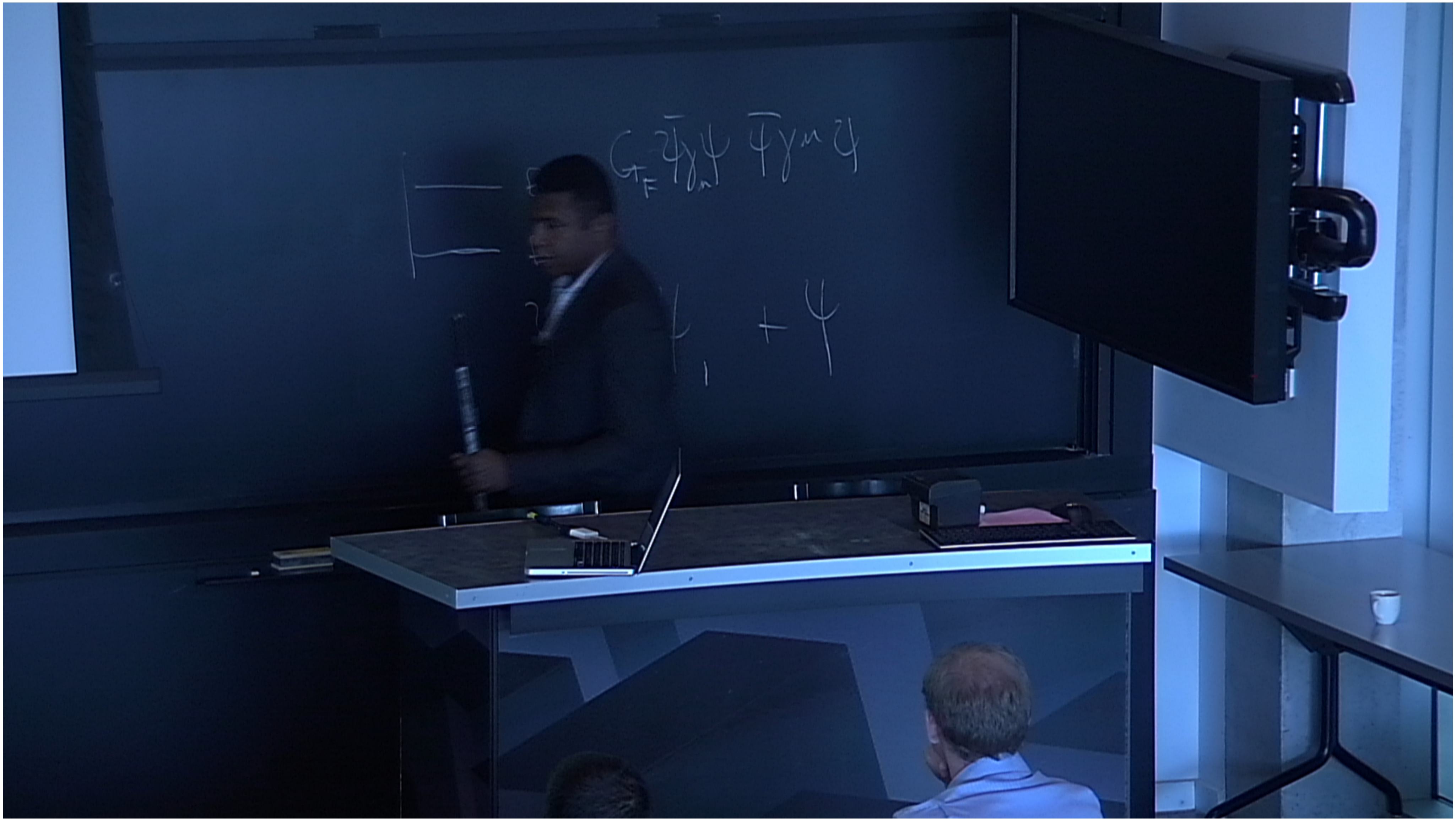
Key point: GR couples to neutrinos via Torsion

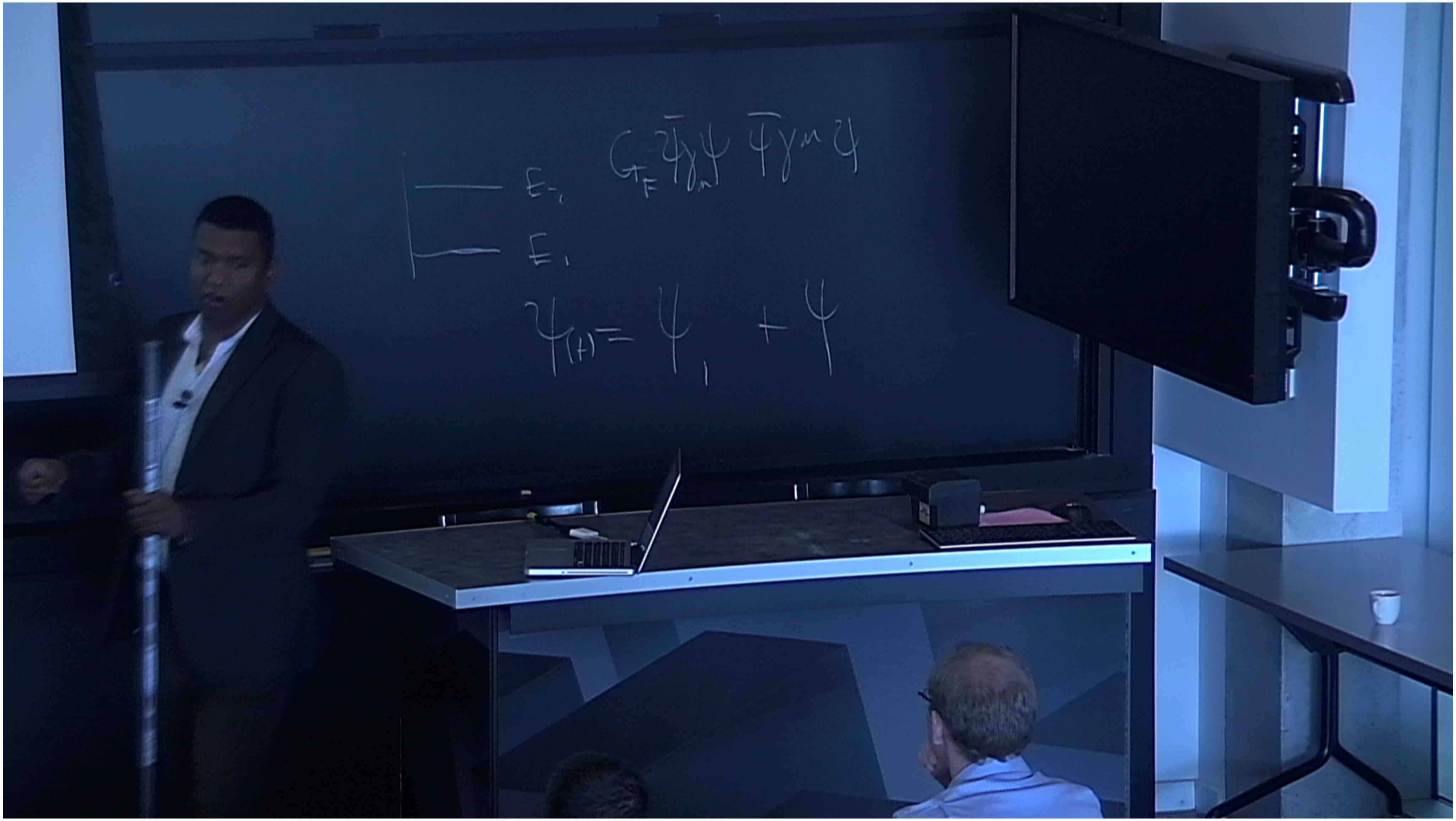
$$S_E = \frac{M_{pl}^2}{2}\int d^4x det(e)\left[R(\omega,e) - \frac{1}{2}\left(i\bar{\psi}\gamma^I e_I^\mu \mathcal{D}_\mu\psi + \text{c.c.}\right)\right]$$

Metric Compatibility Condition $\quad D_{[\mu}e^a_{\nu]} = 0 \quad \omega_\mu^{IJ} = \omega_\mu^{sIJ} + C_\mu^{IJ}$ → Torsion

→ Immirizi Parameter of LQG

$$e_I^\mu C_{\mu JK} = 4\pi G\frac{\gamma^2}{\gamma^2+1}\left(\frac{1}{2}\epsilon_{IJKL}J_5^L - \frac{1}{\gamma}\eta_{I[J}J_{5K]}\right)$$




E_2
$G_F \bar{\psi}\gamma_\mu\psi \, \bar{\psi}\gamma^\mu\psi$
E_1
$\psi(t) = \psi_1 + \psi$

BCS Condensation of Neutrinos

Torsion leads to attractive four fermion interaction

$$S_{int} = \frac{3}{2}\pi G \left(\frac{\gamma^2}{\gamma^2+1}\right) \int d^4x \; e \; J_{5I} J_5^I$$
$$\equiv \frac{1}{M_{Pl}^2} \int d^4x \; e \; \bar{\psi}\gamma_5\gamma^I\psi\bar{\psi}\gamma_5\gamma_I\psi$$

Experimental Fact: If there is a net neutrino number density in early universe, and interaction is attractive neutrinos will condense. (Polchinski '95)

We can calculate the energy gap and effective potential of netrino condensate

Notice, it is Quantum Gravity that determines the attractive nature and strength of coupling! (via. Immirizi)

The first step is to self-consistently find the generating functional for the condition that the auxiliary field $\Delta = \langle \psi^\dagger \psi \rangle$. After expressing the spinors in the Weyl basis and introducing the auxiliary field, the four-fermion generating functional becomes:

$$Z = \int [\mathcal{D}\Delta][\mathcal{D}\xi][\mathcal{D}\zeta] \mathrm{e}^{\mathrm{i}(S_{\mathrm{fer}} + S_{\mathrm{tree}})} \equiv \int [\mathcal{D}\Delta] \mathrm{e}^{\mathrm{i}S_{\mathrm{eff}}} \approx \mathrm{e}^{\mathrm{i}S_{\mathrm{eff}}}\big|_{\mathrm{SP}}$$

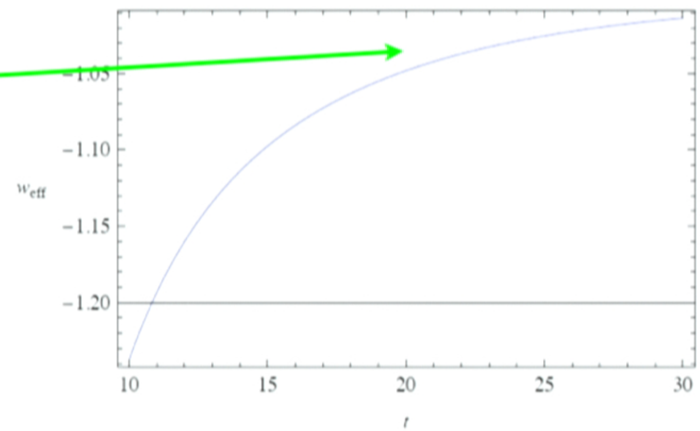
$$\begin{aligned} \rho_{\mathrm{gap}} &= V_{\mathrm{min}} + \mu n \\ &= \frac{\Delta^2}{32\pi^2} \left(\Delta^2 - 8\mu^2\right) \left(2N + 3 + 2 \ln \Delta^2\right) \end{aligned}$$

Dark Energy from Neutrino Condensate

Self consistently solve transendental FRW system

$$H^2 = \frac{8\pi}{3M_{Pl}^2}(\rho_{\rm gap} + \rho_{\rm m}) \qquad \omega(t)_{\rm eff} = -\frac{\ln \rho(\Delta(t))_{\rm gap}}{\ln a(t)} - 1$$

Late Time Acceleration



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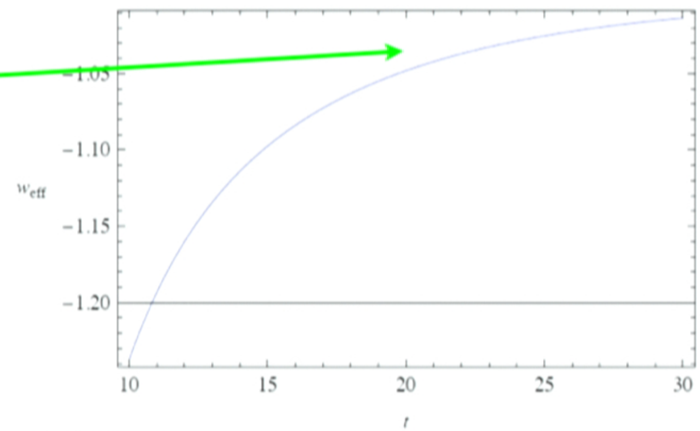

What Happens When Neutrinos Today propigate in their own condensate?

Lets study this theory:

$$\mathcal{L} = \mathrm{i}\bar{\nu}_{\mathrm{A}}\partial_\mu\gamma^\mu\nu_{\mathrm{A}} + \bar{\nu}_{\mathrm{A}}\gamma^\mu\nu_{\mathrm{B}}\Delta_{\mu\mathrm{AB}} + (1+\gamma_5)\Delta_{\mathrm{AB}}\bar{\nu_{\mathrm{A}}}\nu_{\mathrm{B}}.$$

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix} = \left[\frac{\Delta m^2_\Delta}{2E_\nu}\begin{pmatrix} sin^2\theta & cos\theta sin\theta \\ cos\theta sin\theta & cos^2\theta\end{pmatrix}\right. \qquad \text{(IV.32)}$$
$$\left. + \begin{pmatrix}(\Delta + \sqrt{2}G_F N_e) & \Delta_{ex}/2 \\ \Delta^*_{ex}/2 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}.$$

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We get neutrino oscillations that connect oscillation phase to Dark Energy density

$$P_{ex} = P_{xe} \sin^2 2\theta_{\text{eff}} \sin^2 \left(\frac{\Delta_{\text{eff}}}{2} L \right)$$

$$1 + \omega(t)_{\text{eff}} = -\frac{\ln \rho(\Delta(t))_{\text{gap}}}{\ln a(t)}$$

Two Predictions:

I. CPT violating ocsillations

II. Energy Independent Oscillations

(Ando, Kamionkowski, Mocioiu PhysRevD.80.123522

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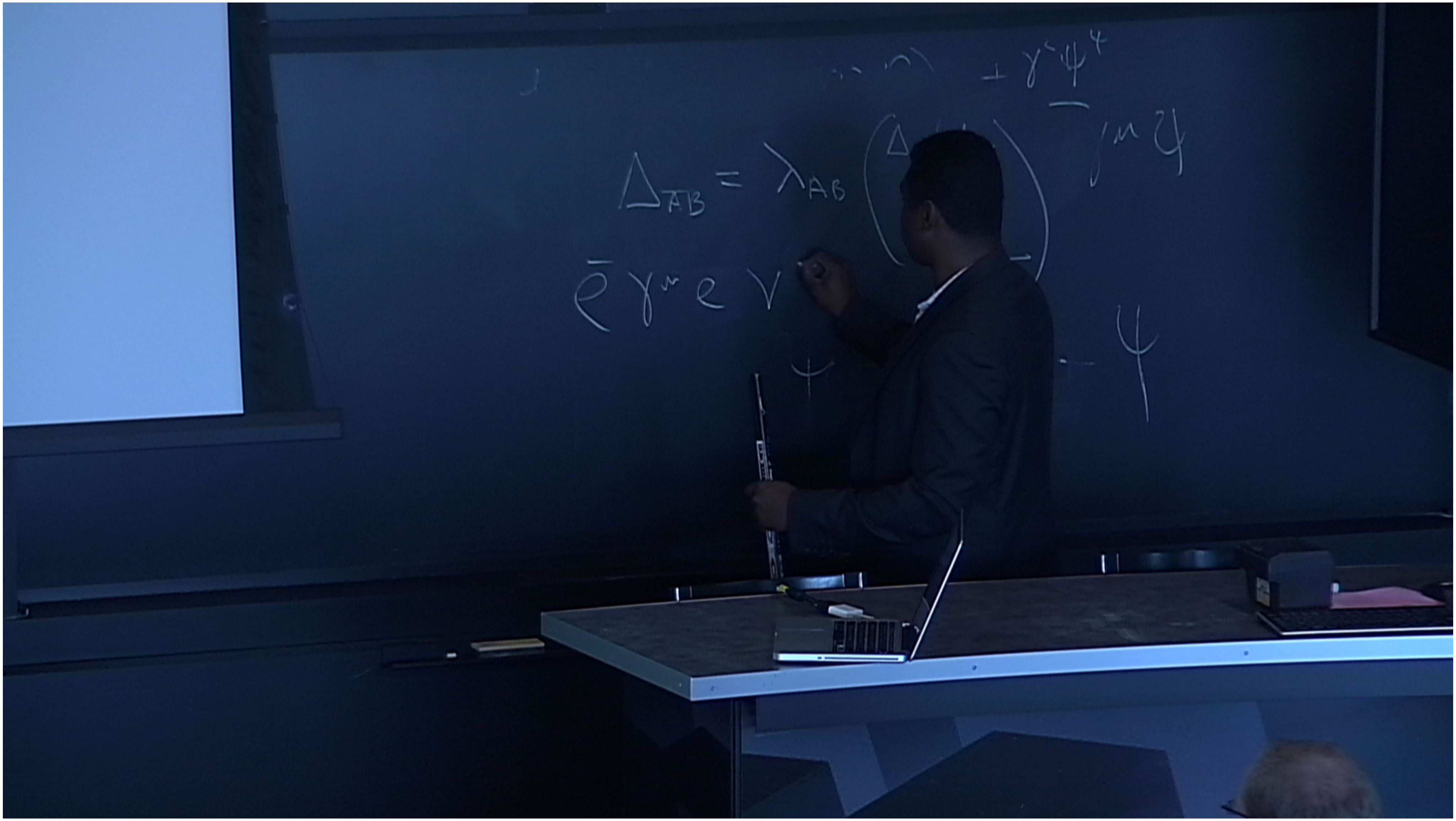

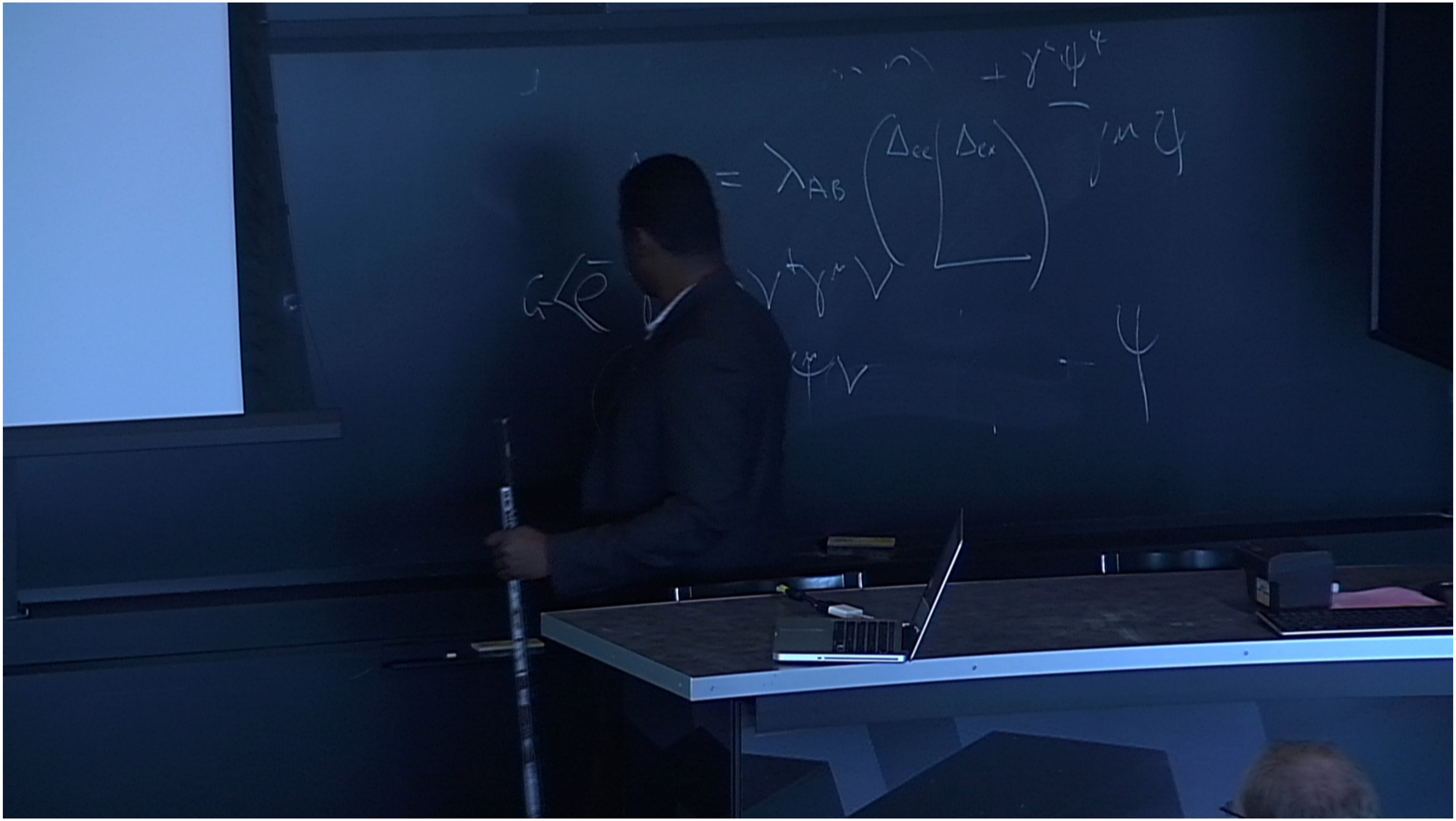

Take 2: Invisible QCD and Dark Energy

(S.A, A. Marciano, D. Spergel, to appear)

Motivation: Dark Energy can't come from visible QCD (Brodsky, Shrock)

We extend the Standard Model with an Invisible QCD sector with dark quarks.

$$\mathcal{L}_{c.n.} = -\left(\frac{R}{2} + \frac{1}{4}F^a{}_{\mu\nu}F_a{}^{\mu\nu} + i\bar{\psi}\partial_\mu\gamma^\mu\psi - eA^a_\mu J^\mu_a + \mathcal{L}_\pi\right)$$

Dark Quarks

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Dark Quarks

Nambu-Jona Lasinio Model

$$\mathcal{L} = \sum_{j=1}^{N} i\bar{\Psi}_j \gamma^\mu D_\mu \Psi_j + \frac{G}{2} \sum_{j=1}^{N} \left[(\bar{\Psi}_j \Psi_j)^2 + (\bar{\Psi}_j i\gamma_5 \Psi_j)^2 \right]$$

Choose condensate VEV $\quad \pi =< \bar{\psi}\gamma_5\psi >$

$$\mathcal{L} = \sum_{j=1}^{N} \left[i\bar{\Psi}_j \gamma^\mu D_\mu \Psi_j - \bar{\Psi}_j(\sigma_j + i\gamma_5\pi_j)\Psi_j - \frac{1}{2G}\left(\sigma_j^2 + \pi_j^2\right) \right]$$

Functional Integration over the ferimon fields

$$\Gamma(\sigma, \pi) = -i \sum_{j=1}^{N} \text{ Tr Ln}\left[i\gamma^\mu D_\mu - (\sigma_j + i\gamma_5\pi_j) \right] - \frac{1}{2G} \int d^4x (\sigma_j^2 + \pi_j^2).$$

Field Equations

Gauge Field

$$\frac{3}{2}\frac{\ddot{\phi}}{a^2} + 6g^2\frac{\phi^3}{a^4} + \frac{3}{2}\frac{H(t)}{a^2}\dot{\phi} - e\bar{J}(a) = 0$$

Pion Condensate

$$\ddot{\pi} + 3H\dot{\pi} + \lambda\,\pi(\pi^2 - f_D^2) = 0$$

Qualitative Understanding of Acceleration

$g^2\phi^3/a^4$ can be neglected, we will find

$$\frac{3}{2}\ddot{\phi} + \frac{3}{2}\dot{\phi}H_0 \simeq ae\bar{J}_0\,,$$

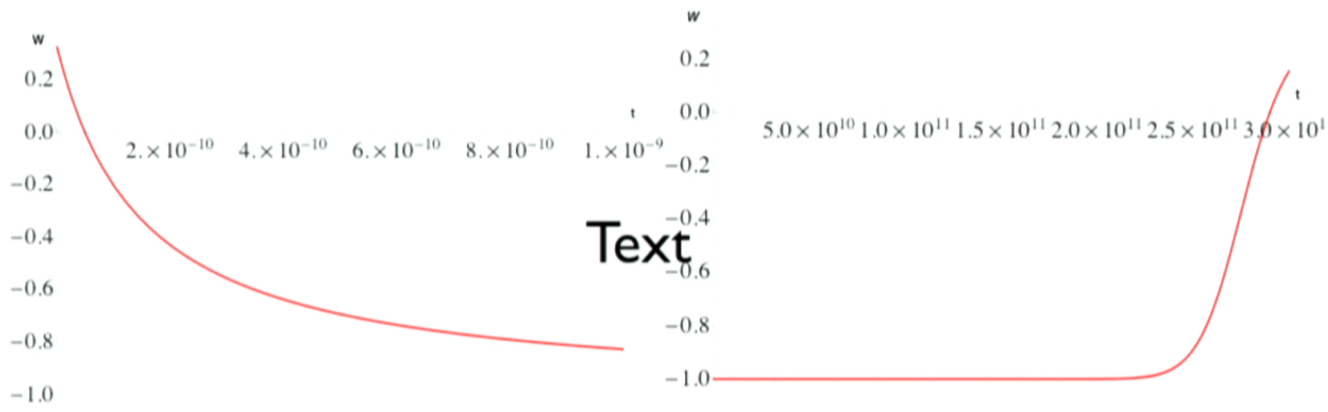
$$w = \frac{P}{\rho} = \frac{\frac{1}{2}\left(\frac{\dot{\phi}^2}{a^2} + \frac{g^2\phi^4}{a^4}\right) - e\phi\bar{J}(a)}{\frac{3}{2}\left(\frac{\dot{\phi}^2}{a^2} + \frac{g^2\phi^4}{a^4}\right) + e\phi\bar{J}(a)}$$

which gives the solution $\phi \simeq a(t)$, if and only if $e\bar{J}_0 \simeq 3H^2$

Interesting Coincidence

$$e\phi_0\langle\bar{\psi}\psi\rangle)^{1/2} \sim 10^{-3}eV$$

Equation of state parameter



$A_0 \simeq 1 \text{ eV}$ $\qquad J_0 \simeq 6g^2 A_0^3 \quad \text{and} \quad \mathcal{H}_0^2 \simeq \frac{6g^2 A_0^4}{\mathcal{M}_p^2}$

Intresting: Scale of QCD 1eV ⟷ $\alpha_{QCD} = 10\alpha_{DQCD}$

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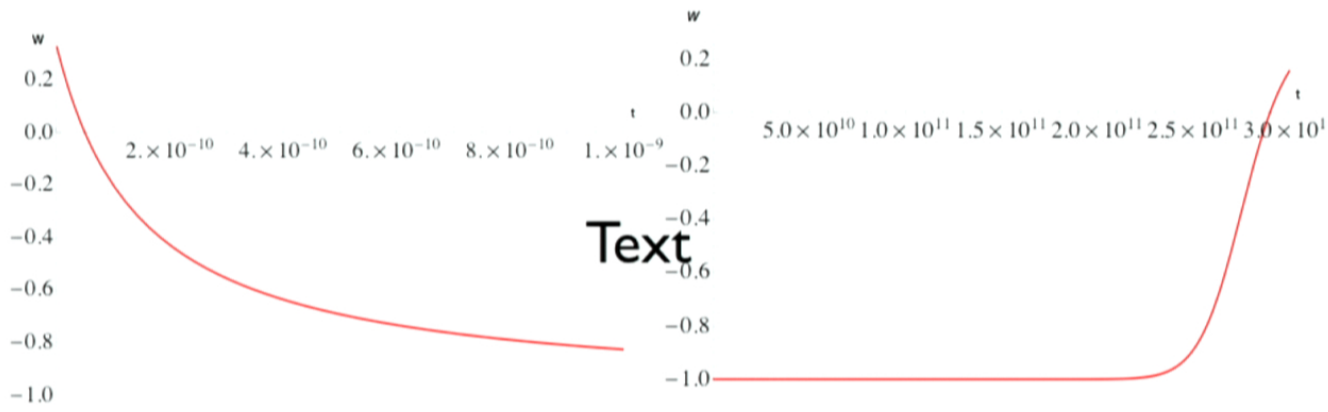

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Stability Analysis:

$$\Box\, \delta A_0^I(\vec{x},\eta) + g\, A(\eta)\epsilon^I{}_{JK}\partial^J \delta A_0^K(\vec{x},\eta) +$$
$$+2g^2 A(\eta)^2 \delta A_0^I(\vec{x},\eta) = q a^4(\eta)\ \delta\pi'^I(\vec{x},\eta)$$

$$\Box\, \delta A_i^I(\vec{x},\eta) + g\, A(\eta)\,[\,\nabla \wedge \delta\vec{A}(\vec{x},\eta)]_i^I +$$
$$+\, g^2\Big[2A^2(\eta)\,\mathrm{Tr}[\delta A(\vec{x},\eta)]\,\delta_i^I\,\Big] = q\, a^4(\eta)\ \partial_i \delta\pi^I(\vec{x},\eta)$$

$$\Box\delta\pi^I(\vec{x},\eta) + 2\frac{a'}{a^2}\,\delta\pi'^I(\vec{x},\eta) + \lambda\,\delta\pi^I(\vec{x},\eta)\left(3\,\pi^2(\eta) - f_D^2\right)$$
$$= -e f_D\ \left(\partial^i \delta A_i^I(\vec{x},\eta) + \delta A'^I_0(\vec{x},\eta)\right)$$

We Get Oscillating solutions for subhorizon modes

Conclusion & Outlook

-Dark Energy from known physics with minimal assumptions about degree of freedom.

-These models have possibility of connecting DE with neutrino oscillation (due to Aether MSW effect).

-More to understand with stability (adiabaticity condtions) and details of microphysics.

(see Afshordi et. al)

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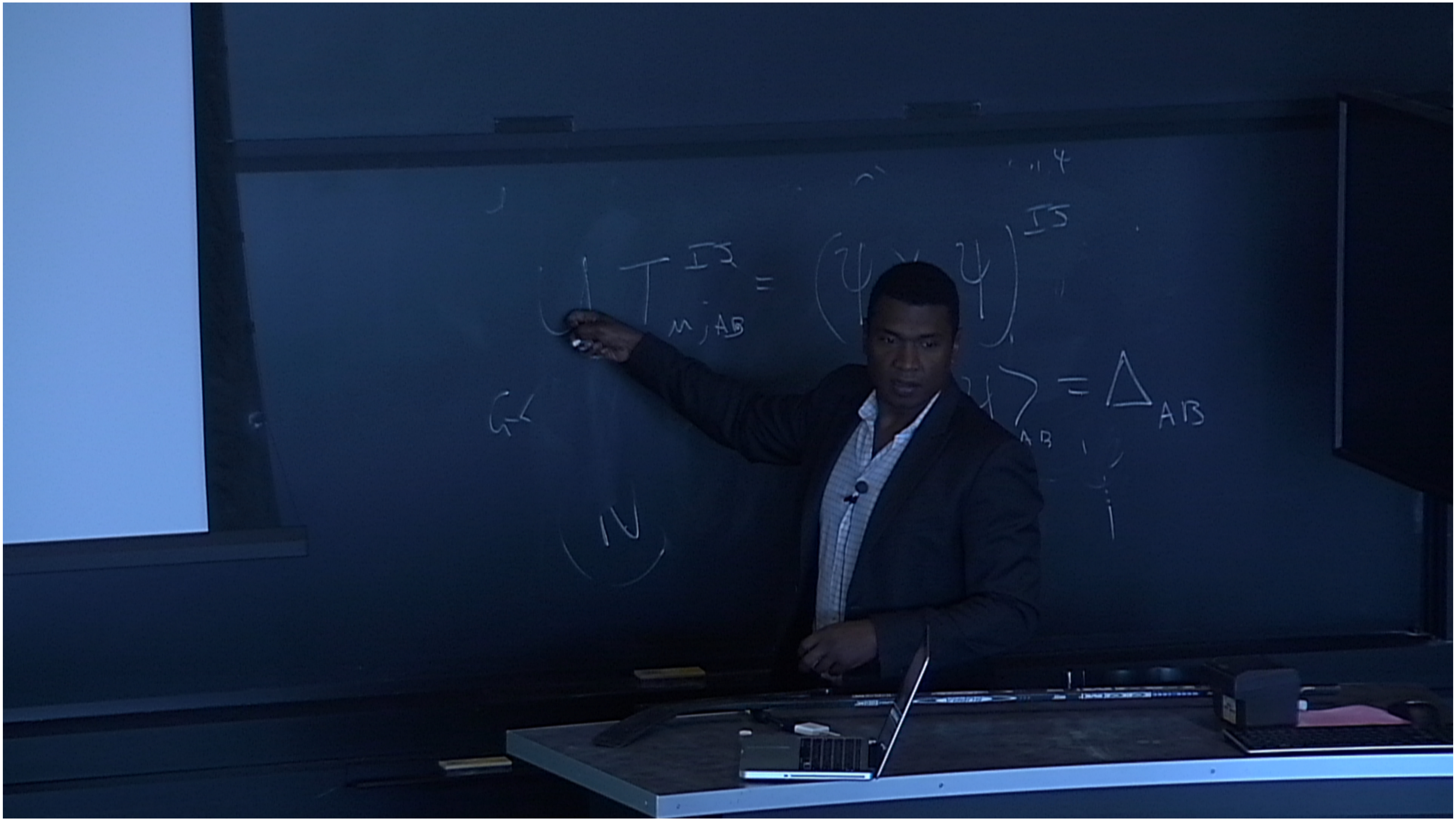
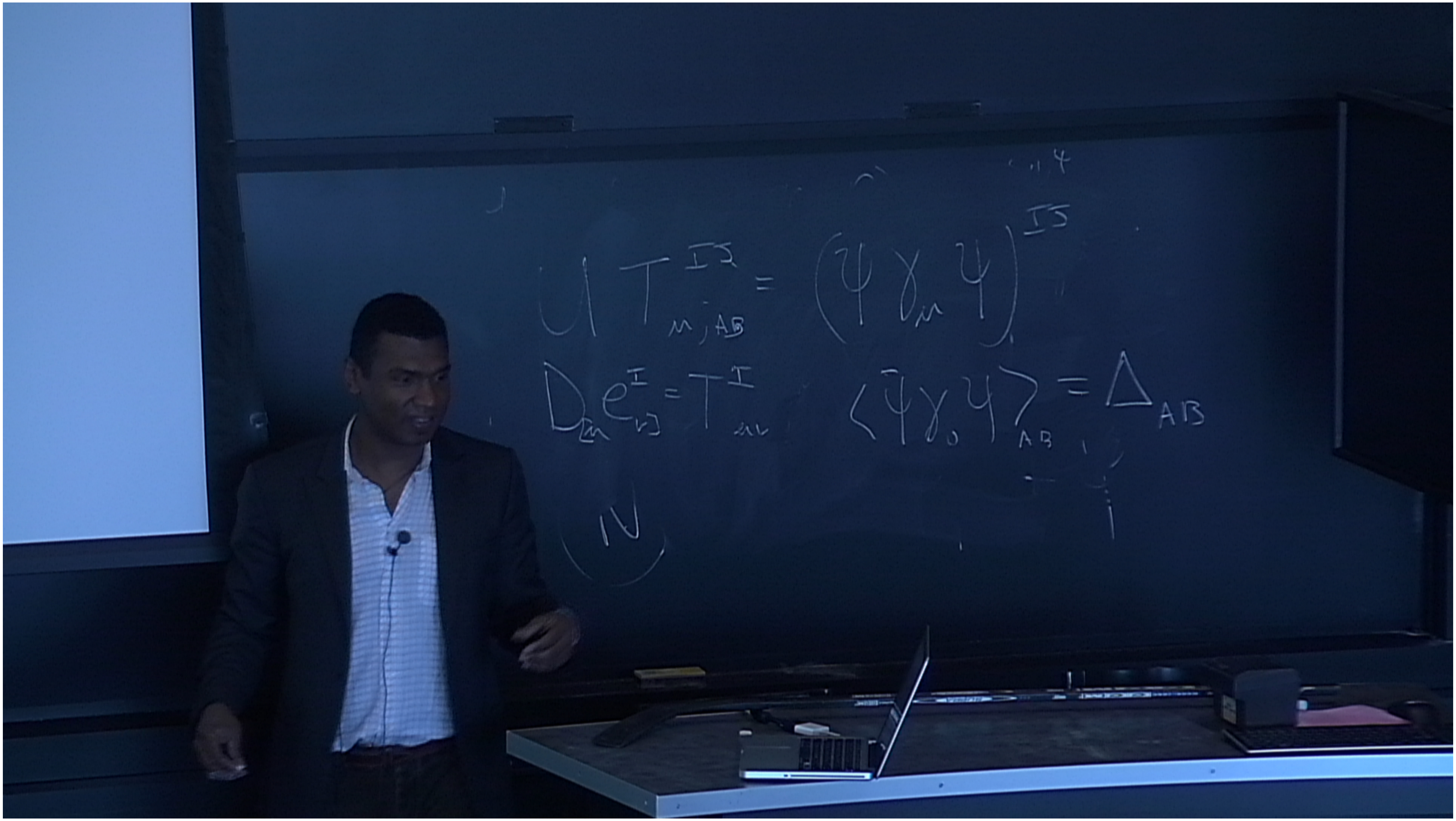




- *What type of music do you listen to?*
- *What is it about this type of music that is appealing?*
- *How varied are your musical tastes?*
- *What musical genres do you really dislike?*


NORTH AMERICAN
MUSIC

- *What type of music do you listen to?*
- *What is it about this type of music that is appealing?*
- *How varied are your musical tastes?*
- *What musical genres do you really dislike?*

WHAT IS MUSIC?

- Music is defined as a combination of sounds that create a rhythm, symphony, or melody.

How Is Music Categorized?

- Music is a broad category; therefore, it is divided into many categories known as genres.
- Each genre is a different style of music.
- All of these genres have been separated, named, and identified because they appeal to different audiences.
- There's not one genre that is better or worse, or that is more or less creative. They differ a lot in melody and lyric style, themes, rhythm, and production and each one has an audience that likes a certain sound.


TYPES OF MUSIC
Hip Hop
R & B also known as Rhythm & Blues
Country
Rock
Alternative Rock
Heavy Metal
Classical Music
Punk Rock
Dance/ Electronic

Where Can Music Be Heard?

Backyards, playgrounds, school, mp3s, computer, hospital, house, work, clubs. Due to today's technology music can now be heard ANYWHERE!!

Well Known North American Musicians

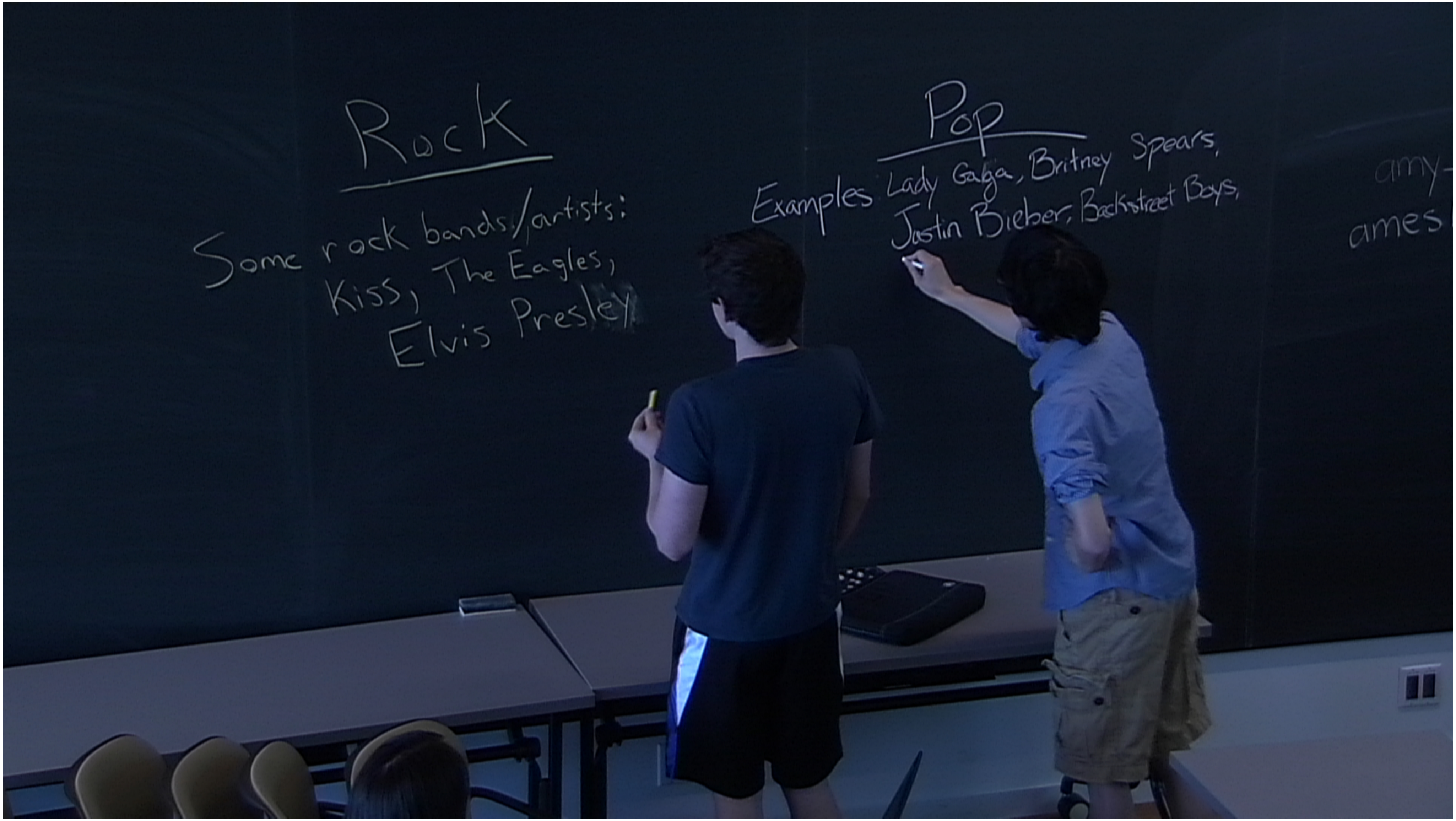


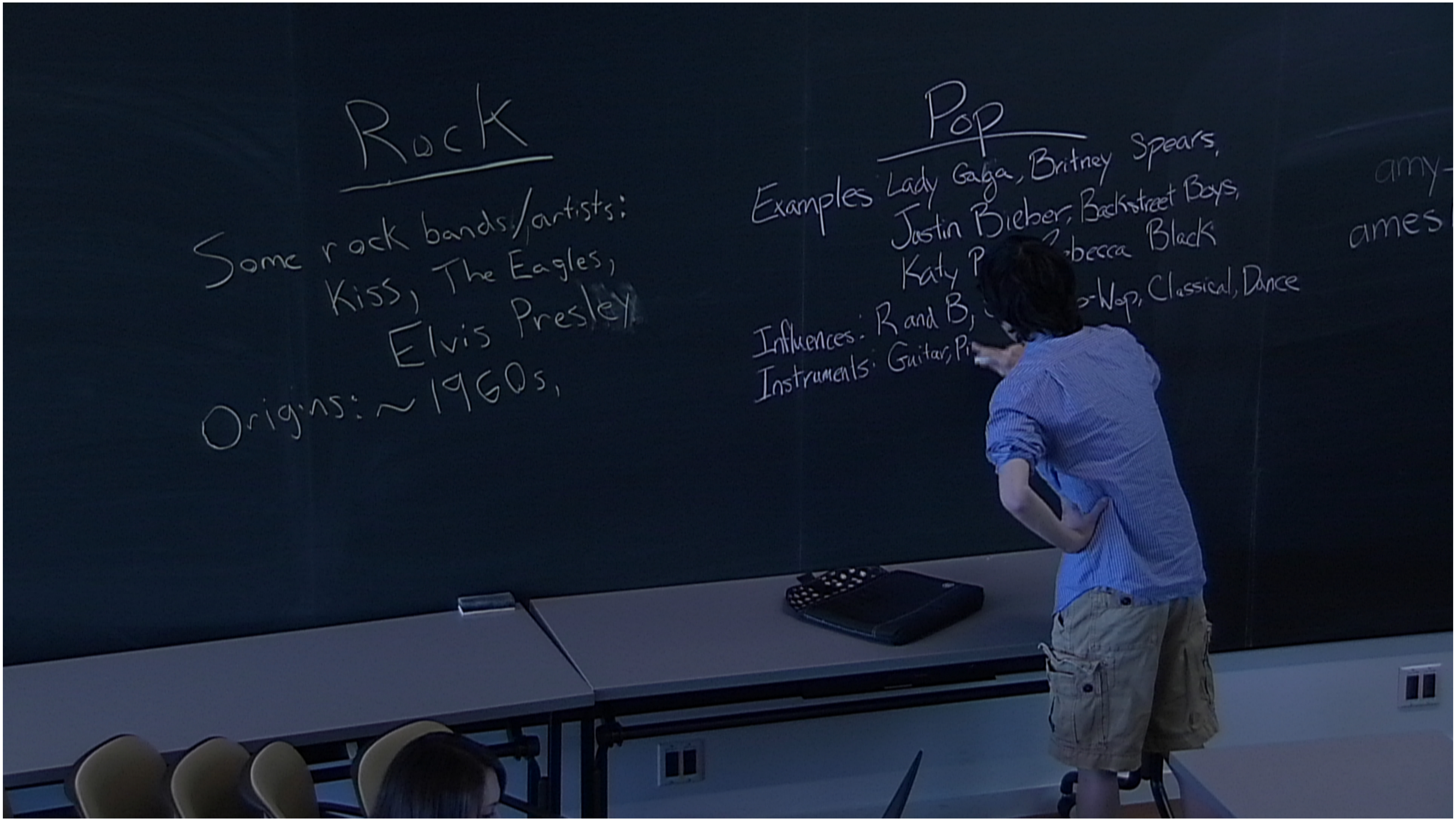




NAME THAT
TUNE!
TUESDAY


YOUR TASK
Each group is responsible for investigating a specific genre of music and presenting the information found to the class.
Groups should provide information such as:
Top Artists
New Releases
Instruments used
Origin
Moods/Themes
The music genres we will research are: Pop, Country, Rock, Hip Hop, Classical.
You can find these genres at:
http://www.allmusic.com/


Rock
Some rock bands/artists:
Kiss, The Eagles,
Elvis Presley
Pop
Examples: Lady Gaga, Britney Spears,
Justin Bieber, Backstreet Boys,


Rock
Some rock bands/artists:
Kiss, The Eagles,
Elvis Presley
Origins: ~1960s,
Pop
Examples: Lady Gaga, Britney Spears,
Justin Bieber, Backstreet Boys,
Katy P
ebecca Black
Influences: R and B,
o-Wop, Classical, Dance
Instruments: Guitar, Pi
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REFLECTION

- Each student in the group must hand in a one-page reflection on the project using these guided reflection questions:

- *What were the three most important and/or interesting things you learned about this genre of music?*

- *Explain why you think someone would listen/like this genre of music?*