INVISIBLE UNIVERSE
Palais de l'UNESCO, PARIS, FRANCE

June 29 - July 3, 2009

NATURAL NEUTRINO DARK ENERGY

Ilya Gurwich
Physics Department
Ben-Gurion University

Outline

* Motivation
* Some general results for a new class of models
* Results vs measurements
* An example model
* Results vs measurements
* Open question and future research

Motivation - The Dark Energy Puzzle

It is unnecessary to talk about the importance or the problems of the dark energy in front of the audience before me...

Motivation - The Dark Energy Puzzle

It is unnecessary to talk about the importance or the problems of the dark energy in front of the audience before me...

So let me just begin by sharing some personal views...

Motivation - The Dark Energy Puzzle

It is unnecessary to talk about the importance or the problems of the dark energy in front of the audience before me...

So let me just begin by sharing some personal views...

With countless theoretical possibilities
A vast array of dark energy models arose since the original observational evidence:

Motivation - The Dark Energy Puzzle

It is unnecessary to talk about the importance or the problems of the dark energy in front of the audience before me...

So let me just begin by sharing some personal views...

With countless theoretical possibilities
A vast array of dark energy models arose since the original observational evidence:
cosmological constant, quintessence, DGP self-acceleration, vacuum-energy, MaVaNs and many many more...

Motivation - The Dark Energy Puzzle

It is unnecessary to talk about the importance or the problems of the dark energy in front of the audience before me...

So let me just begin by sharing some personal views...

With countless theoretical possibilities
A vast array of dark energy models arose since the original observational evidence:
cosmological constant, quintessence, DGP self-acceleration, vacuum-energy, MaVaNs and many many more...

Despite improving observational constraints, constantly used to sort the different models, “theoreticians work faster”.

It is important to see whether we can solve dark energy without invoking new physics and new particles. And what is the most we can say without constraining ourselves to a specific model.

Motivation - Energy Scales

so how does dark energy fit into what we already know?

Motivation - Energy Scales

so how does dark energy fit into what we already know?

- $\Lambda \sim (10^{-33}eV)^2$: No known scale to match.
- $\rho_\Lambda \sim (10^{-3}eV)^4$: The lightest neutrino mass, m_ν, matches the scale. **The only fundamental scale** that matches.
- There are other complex/composite (non-fundamental) scales that match this value, for example: $\Lambda_{QCD}^2/M_{plank}$

Motivation - Existing Models

Motivation - Existing Models

- MaVaNs - Fardon, Nelson, Weiner (2004,2006), Peccei (2005), Horvat (2006) and many more...

Motivation - Existing Models

* MaVaNs - Fardon, Nelson, Weiner (2004,2006), Peccei (2005), Horvat (2006) and many more...
* Neutrino mixing - Blasone, Capolupo, Capozziello, Carloni, Vitiello (2004-2007) and many more...

Motivation - Existing Models

- MaVaNs - Fardon, Nelson, Weiner (2004,2006), Peccei (2005), Horvat (2006) and many more...
- Neutrino mixing - Blasone, Capolupo, Capozziello, Carloni, Vitiello (2004-2007) and many more...
- Different attempts - Guendelman, Kaganovich (2004), de Vega, Sanchez (2007), Bamba, Geng, Ho (2008) and many more...

Motivation - Existing Models

* **MaVaNs** - Fardon, Nelson, Weiner (2004,2006), Peccei (2005), Horvat (2006) and many more...
* **Neutrino mixing** - Blasone, Capolupo, Capozziello, Carloni, Vitiello (2004-2007) and many more...
* **Different attempts** - Guendelman, Kaganovich (2004), de Vega, Sanchez (2007), Bamba, Geng, Ho (2008) and many more...

All models suffer from one common problem
What is so special about the neutrino?

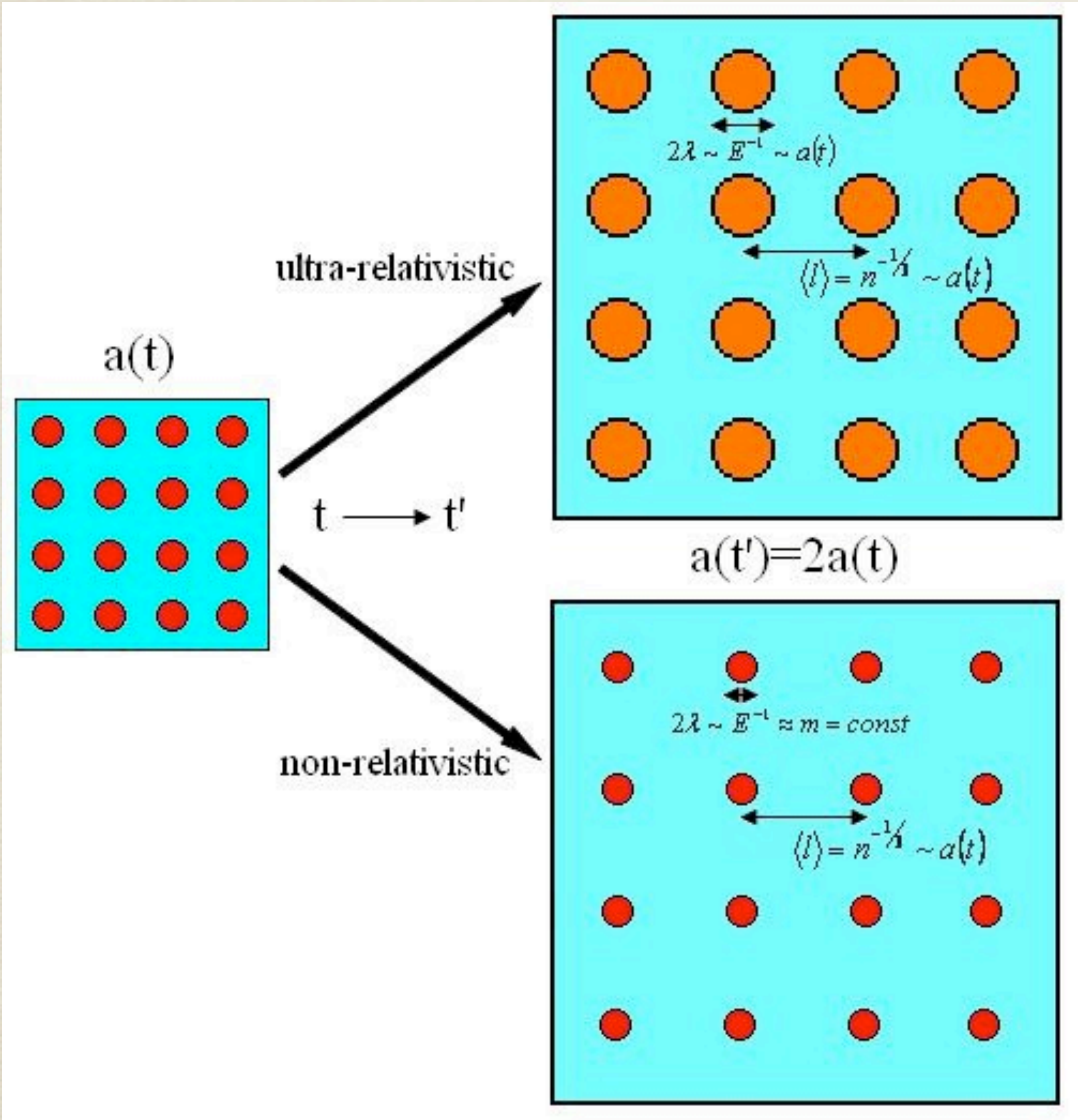
In search of a natural model

- The lightest neutrino is (probably) the only massive particles that is still relativistic... So what?
- non-relativistic particles have a relatively constant energy $\simeq$ m.
- relativistic particles have an energy that changes as the universe expands $\sim a(t)^{-1}$.

In search of a natural model

- From a QFT point of view, one may view the particles as spheres of size E^{-1}, where E is the particle energy.
- For relativistic particles, the concentrations of these spheres $\sim a^3 N (E^{-1})^3 \propto (El)^{-3}$ (N is the number of particles and l is the mean distance between them), meaning the relative space they occupy is constant as the universe expands.
- It is also important to note that the quantity El, governs the propagation of the particles over the average distance between them l, so it is expected to govern any relevant interaction that is expected to lead to the dark energy contribution.

In search of a natural model



For relativistic particles, the situation stays constant in the comoving frame.

For non-relativistic particles, from the comoving frame, it seems as if they disappear, any interaction between them would weaken.

In search of a natural model

* Another relevant parameter that behaves as a constant for relativistic particles and grows for non-relativistic ones is E/T.

* This factor may become relevant for creation and annihilation operators of states that generate the dark energy, as $\exp(-E/T)$.

A General Natural Model

A General Natural Model

Assuming: $\rho_{DE} = \sum_{fermions} f(\xi_i)$

Where: $\xi_i = E_i/T_i$ **or** $\xi_i = E_i l_i$

A General Natural Model

Assuming: $\rho_{DE} = \sum_{fermions} f(\xi_i)$

Where: $\xi_i = E_i/T_i$ **or** $\xi_i = E_i l_i$

For the dark energy to be naturally related to relativistic particles and fit the mass scale, we also assume:

$$\lim_{x \to 0} f(x) \sim m^4 \quad \textbf{and} \quad \lim_{x \to \infty} f(x) = 0$$

A General Natural Model

A General Natural Model

Assuming: $\rho_{DE} = f(E_\nu l_\nu)$

A General Natural Model

Assuming: $\rho_{DE} = f(E_\nu l_\nu)$ $\qquad l_\nu = \frac{1}{n_\nu^{1/3}} \quad E_\nu = \frac{\rho_\nu}{n_\nu}$

A General Natural Model

Assuming: $\rho_{DE} = f(E_\nu l_\nu)$ $\quad l_\nu = \frac{1}{n_\nu^{1/3}} \quad E_\nu = \frac{\rho_\nu}{n_\nu}$

We have:

$$1 + w_{DE} = -\frac{1}{3}\frac{a}{\rho_{DE}}\frac{\partial \rho_{DE}}{\partial a} = -\frac{1}{3}\frac{a}{\rho_{DE}} f'(E_\nu l_\nu)\frac{\partial (E_\nu l_\nu)}{\partial a}$$

A General Natural Model

Assuming: $\rho_{DE} = f(E_\nu l_\nu)$ $\qquad l_\nu = \frac{1}{n_\nu^{1/3}} \qquad E_\nu = \frac{\rho_\nu}{n_\nu}$

We have:

$$1 + w_{DE} = -\frac{1}{3}\frac{a}{\rho_{DE}}\frac{\partial \rho_{DE}}{\partial a} = -\frac{1}{3}\frac{a}{\rho_{DE}} f'(E_\nu l_\nu)\frac{\partial (E_\nu l_\nu)}{\partial a}$$

$$n_\nu = 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{1}{1+\exp(p/T_\nu)}$$

A General Natural Model

Assuming: $\rho_{DE} = f(E_\nu l_\nu)$ $\quad l_\nu = \frac{1}{n_\nu^{1/3}}$ $\quad E_\nu = \frac{\rho_\nu}{n_\nu}$

We have:

$$1 + w_{DE} = -\frac{1}{3}\frac{a}{\rho_{DE}}\frac{\partial \rho_{DE}}{\partial a} = -\frac{1}{3}\frac{a}{\rho_{DE}} f'(E_\nu l_\nu)\frac{\partial (E_\nu l_\nu)}{\partial a}$$

$$n_\nu = 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{1}{1+\exp(p/T_\nu)}$$

$$\rho_\nu = 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{\sqrt{p^2+m_\nu^2}}{1+\exp(p/T_\nu)} \simeq 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{p+\frac{m_\nu^2}{2p}}{1+\exp(p/T_\nu)}$$

Assuming $1 + w_{DE} << 1$

A General Natural Model

A General Natural Model

Eventually we have: $$E_\nu l_\nu \simeq \alpha + \beta \left(\frac{m_\nu}{T_\nu}\right)^2$$

$$\alpha = \frac{7}{90}\left(\frac{\pi^{14}}{12\zeta(3)^4}\right)^{1/3} \simeq 5.554 \qquad \beta = \frac{1}{18}\left(\frac{\pi^{8}}{12\zeta(3)^4}\right)^{1/3} \simeq 0.402$$

$$1 + w_{DE} \simeq -\frac{2\beta}{3}\frac{f'(E_\nu l_\nu)}{f(E_\nu l_\nu)}\left(\frac{m_\nu}{T_\nu}\right)^2$$

A General Natural Model

Eventually we have: $E_\nu l_\nu \simeq \alpha + \beta \left(\frac{m_\nu}{T_\nu}\right)^2$

$$\alpha = \frac{7}{90}\left(\frac{\pi^{14}}{12\zeta(3)^4}\right)^{1/3} \simeq 5.554 \qquad \beta = \frac{1}{18}\left(\frac{\pi^{8}}{12\zeta(3)^4}\right)^{1/3} \simeq 0.402$$

$$1 + w_{DE} \simeq -\frac{2\beta}{3}\frac{f'(E_\nu l_\nu)}{f(E_\nu l_\nu)}\left(\frac{m_\nu}{T_\nu}\right)^2$$

Assuming $1 + w_{DE} << 1$:

A General Natural Model

Eventually we have: $E_\nu l_\nu \simeq \alpha + \beta \left(\frac{m_\nu}{T_\nu}\right)^2$

$$\alpha = \frac{7}{90}\left(\frac{\pi^{14}}{12\zeta(3)^4}\right)^{1/3} \simeq 5.554 \qquad \beta = \frac{1}{18}\left(\frac{\pi^{8}}{12\zeta(3)^4}\right)^{1/3} \simeq 0.402$$

$$1 + w_{DE} \simeq -\frac{2\beta}{3}\frac{f'(E_\nu l_\nu)}{f(E_\nu l_\nu)}\left(\frac{m_\nu}{T_\nu}\right)^2$$

Assuming $1 + w_{DE} << 1$:

$$\frac{\partial w_{DE}}{\partial z} \simeq \frac{4\beta}{3}\frac{f'(E_\nu l_\nu)}{f(E_\nu l_\nu)}\left(\frac{m_\nu}{T_\nu}\right)^2 = -2(1 + w_{DE})$$

A General Natural Model

Assuming: $\rho_{DE} = f(E_\nu/T_\nu)$

$$E_\nu = \frac{\rho_\nu}{n_\nu}$$

We have:

$$1 + w_{DE} = -\frac{1}{3}\frac{a}{\rho_{DE}}\frac{\partial \rho_{DE}}{\partial a} = -\frac{1}{3}\frac{a}{\rho_{DE}} f'(E_\nu/T_\nu)\frac{\partial (E_\nu/T_\nu)}{\partial a}$$

$$n_\nu = 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{1}{1+\exp(p/T_\nu)}$$

$$\rho_\nu = 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{\sqrt{p^2+m_\nu^2}}{1+\exp(p/T_\nu)} \simeq 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{p+\frac{m_\nu^2}{2p}}{1+\exp(p/T_\nu)}$$

Assuming $1 + w_{DE} << 1$

A General Natural Model

Eventually we have: $E_\nu/T_\nu \simeq \alpha + \beta\left(\frac{m_\nu}{T_\nu}\right)^2$

$$\alpha = \frac{7\pi^4}{180\zeta(3)} \simeq 3.151 \qquad \beta = \frac{5\pi^2}{180\zeta(3)} \simeq 0.228$$

$$1 + w_{DE} \simeq -\frac{2\beta}{3}\frac{f'(E_\nu/T_\nu)}{f(E_\nu/T_\nu)}\left(\frac{m_\nu}{T_\nu}\right)^2$$

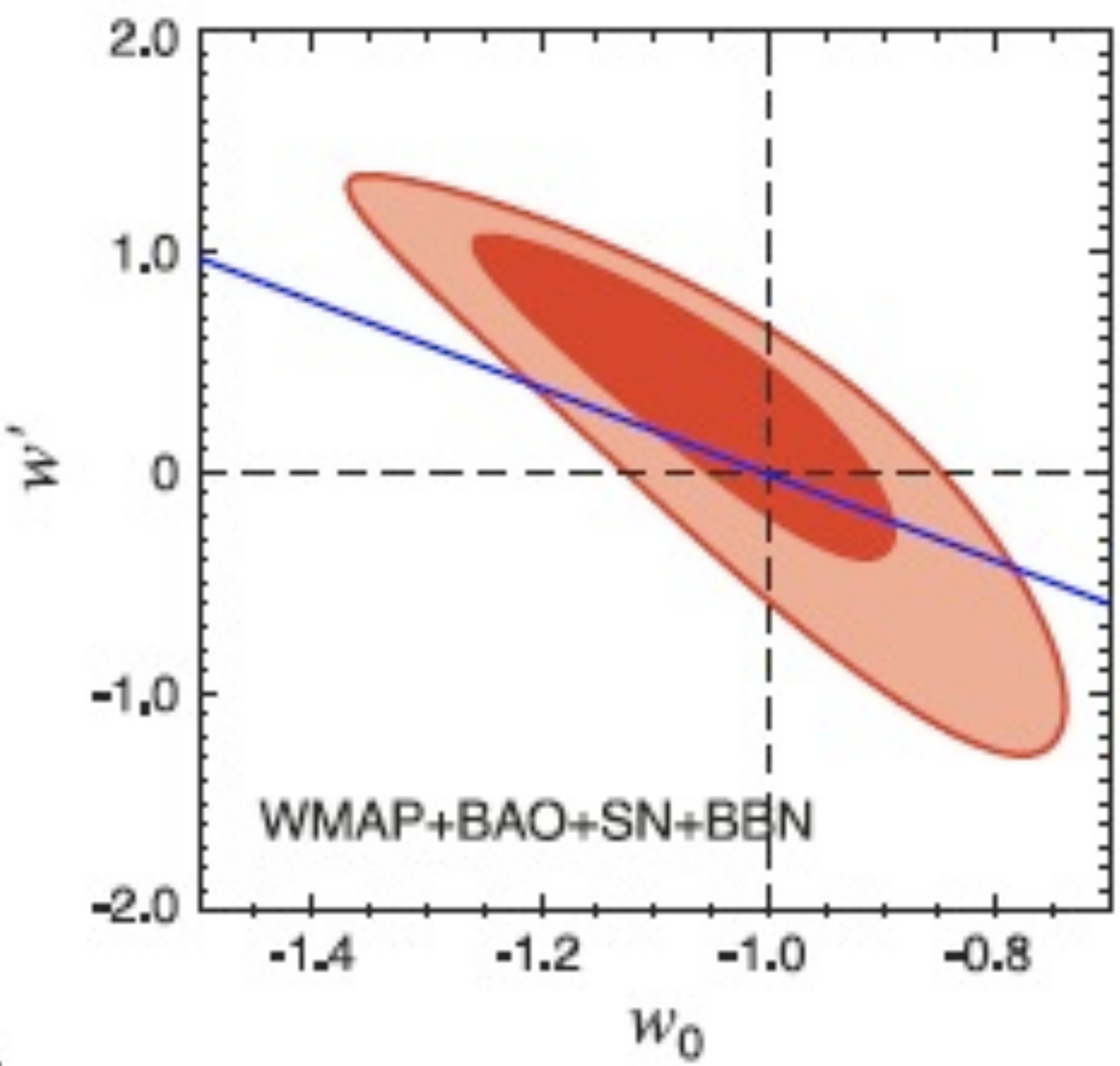
Assuming $1 + w_{DE} << 1$:

$$\frac{\partial w_{DE}}{\partial z} \simeq -\frac{4\beta}{3}\frac{f'(E_\nu/T_\nu)}{f(E_\nu/T_\nu)}\left(\frac{m_\nu}{T_\nu}\right)^2 = -2(1 + w_{DE})$$

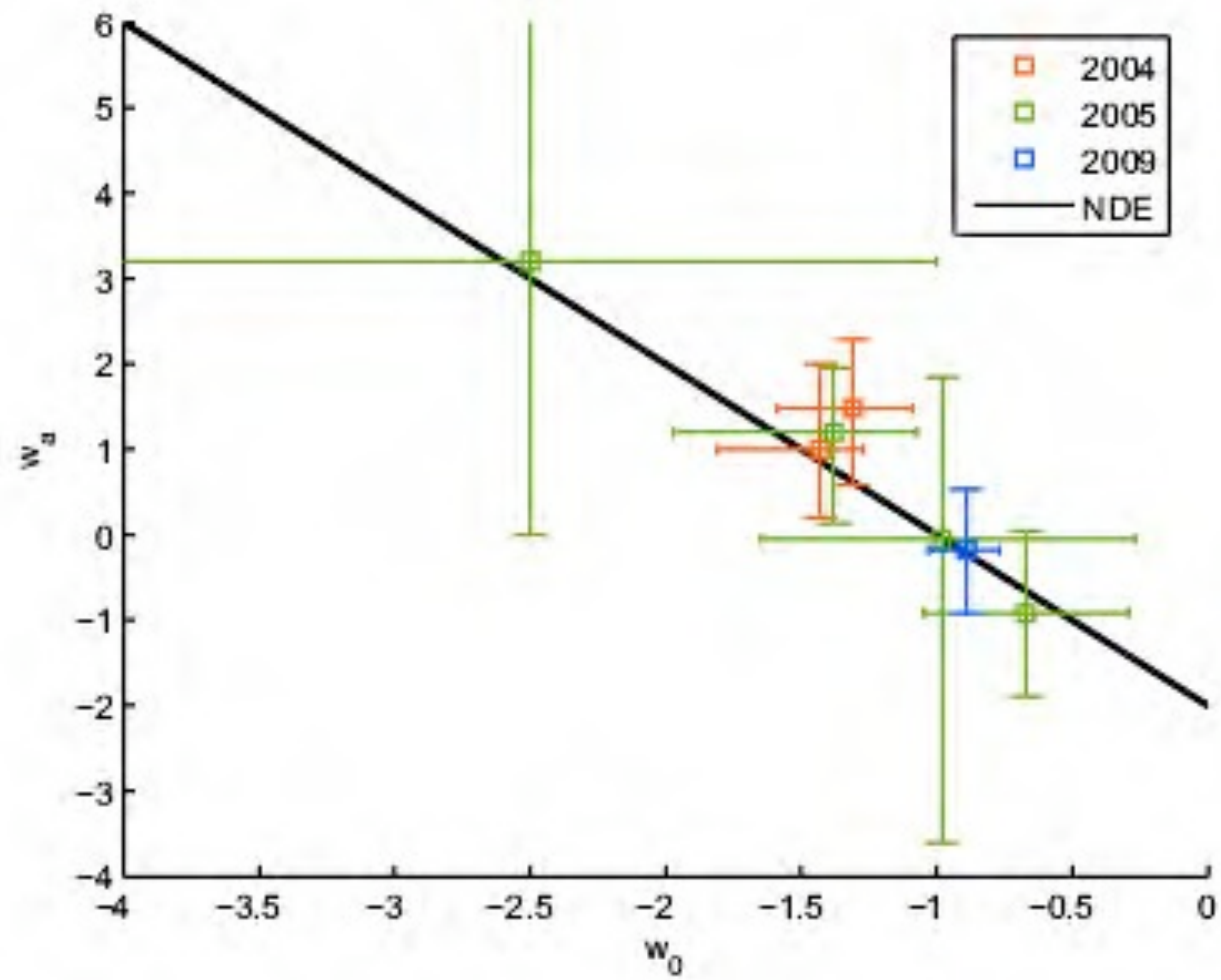
Natural Neutrino Dark Energy - Results vs Observations

Conventional notations: $w_a = -2(1 + w_0)$

from E. Komatsu et al. (5 year WMAP)



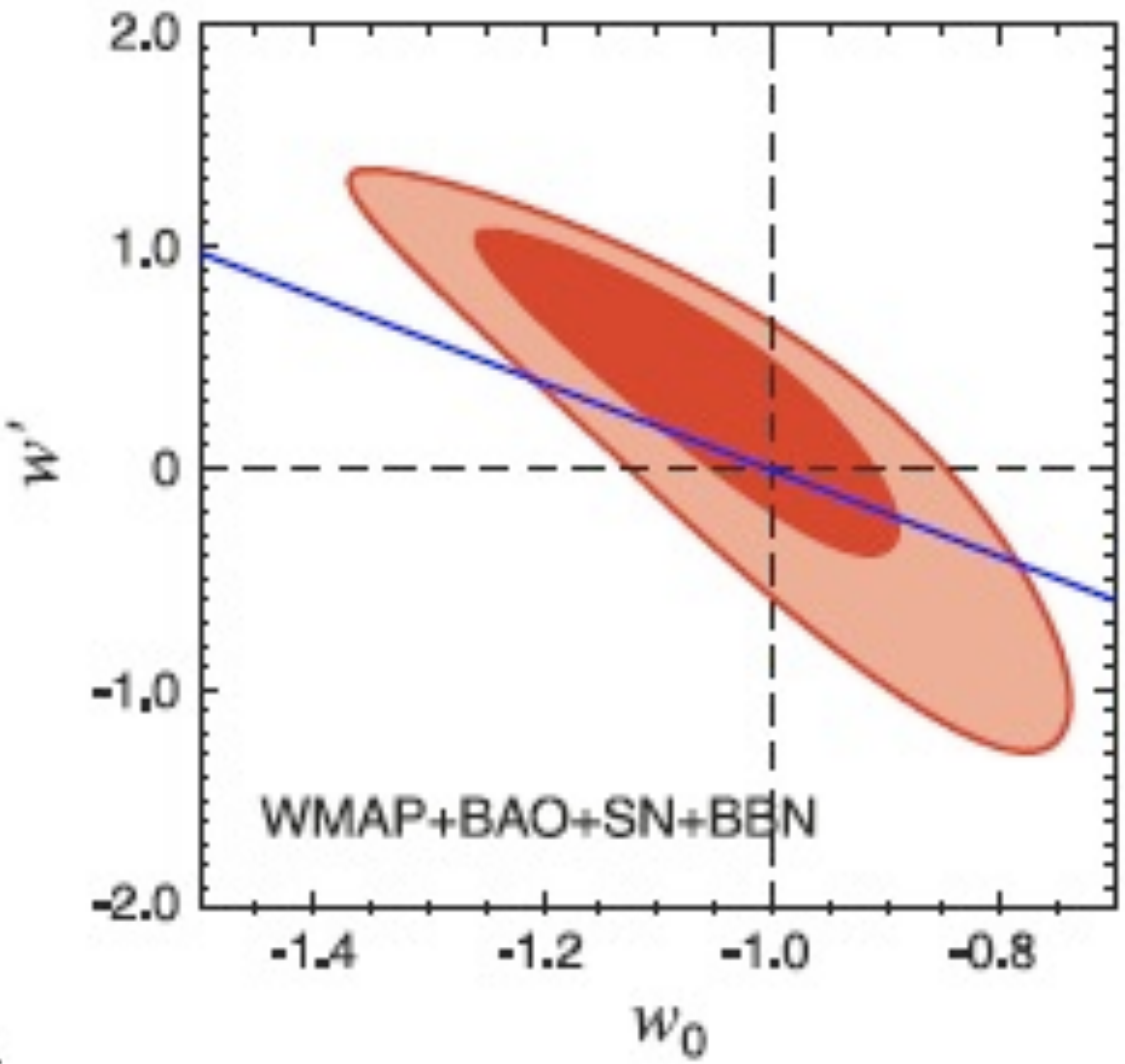
from different papers throughout the years



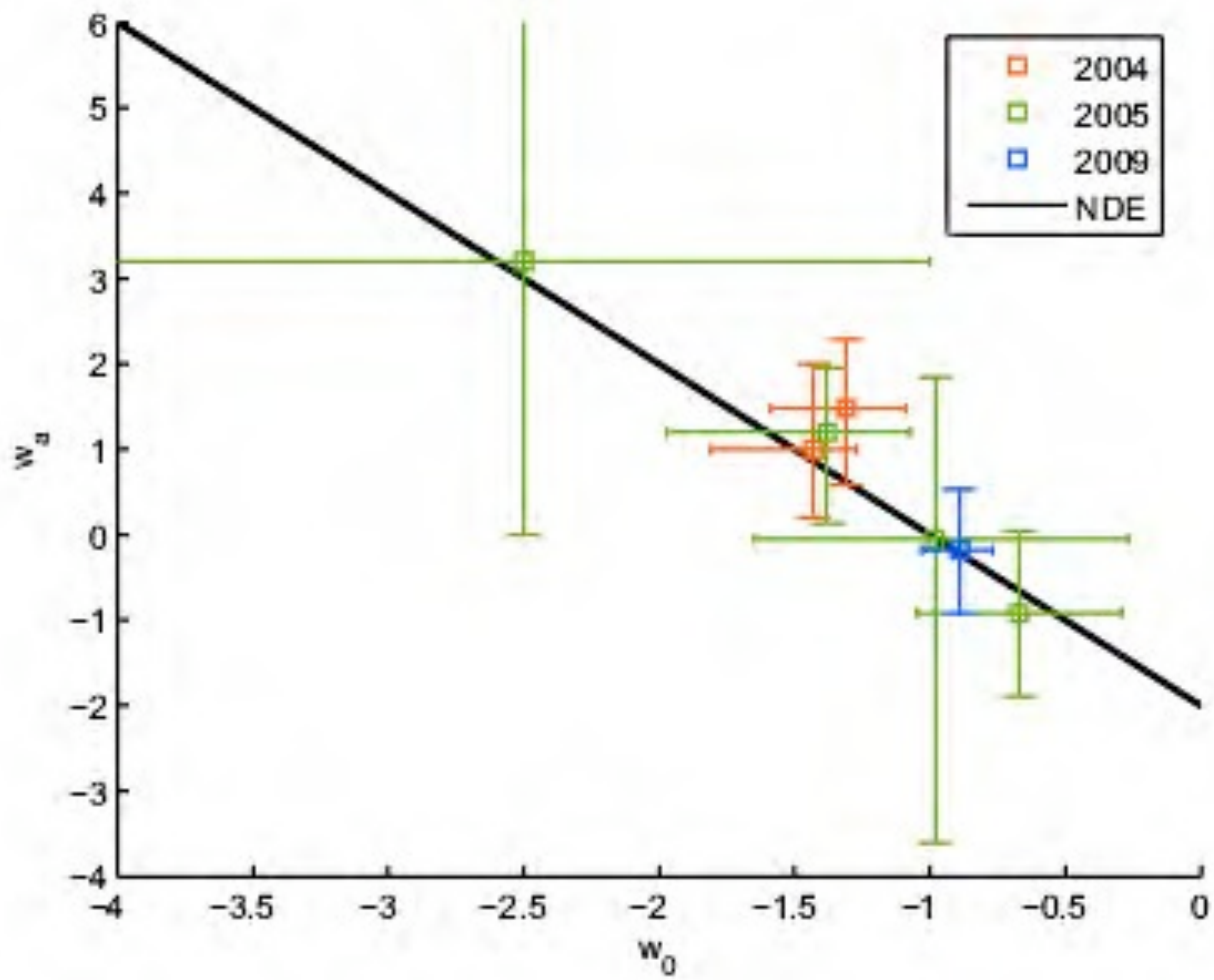
Natural Neutrino Dark Energy - Results vs Observations

Conventional notations: $w_a = -2(1 + w_0)$

from E. Komatsu et al. (5 year WMAP)

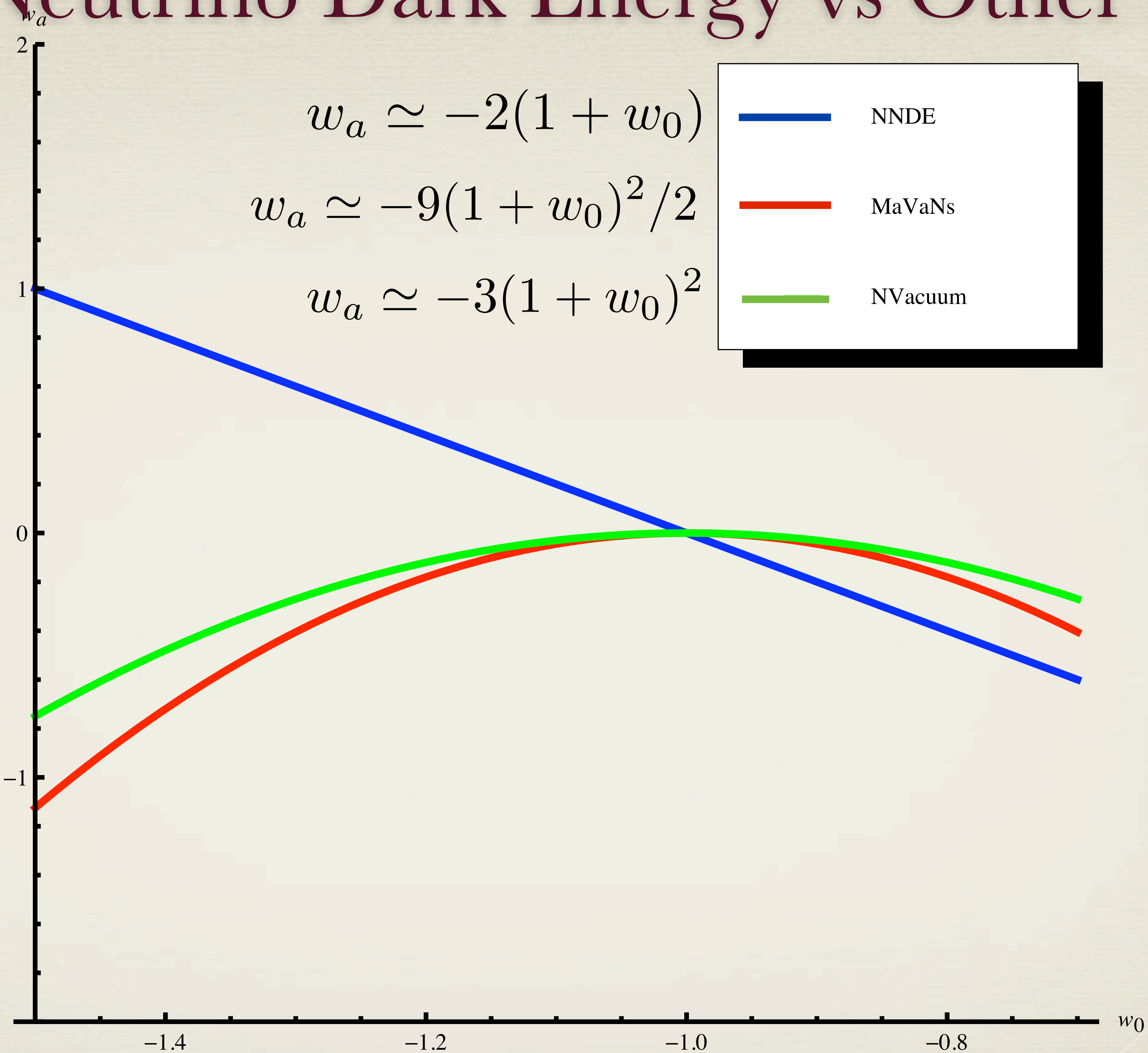


from different papers throughout the years

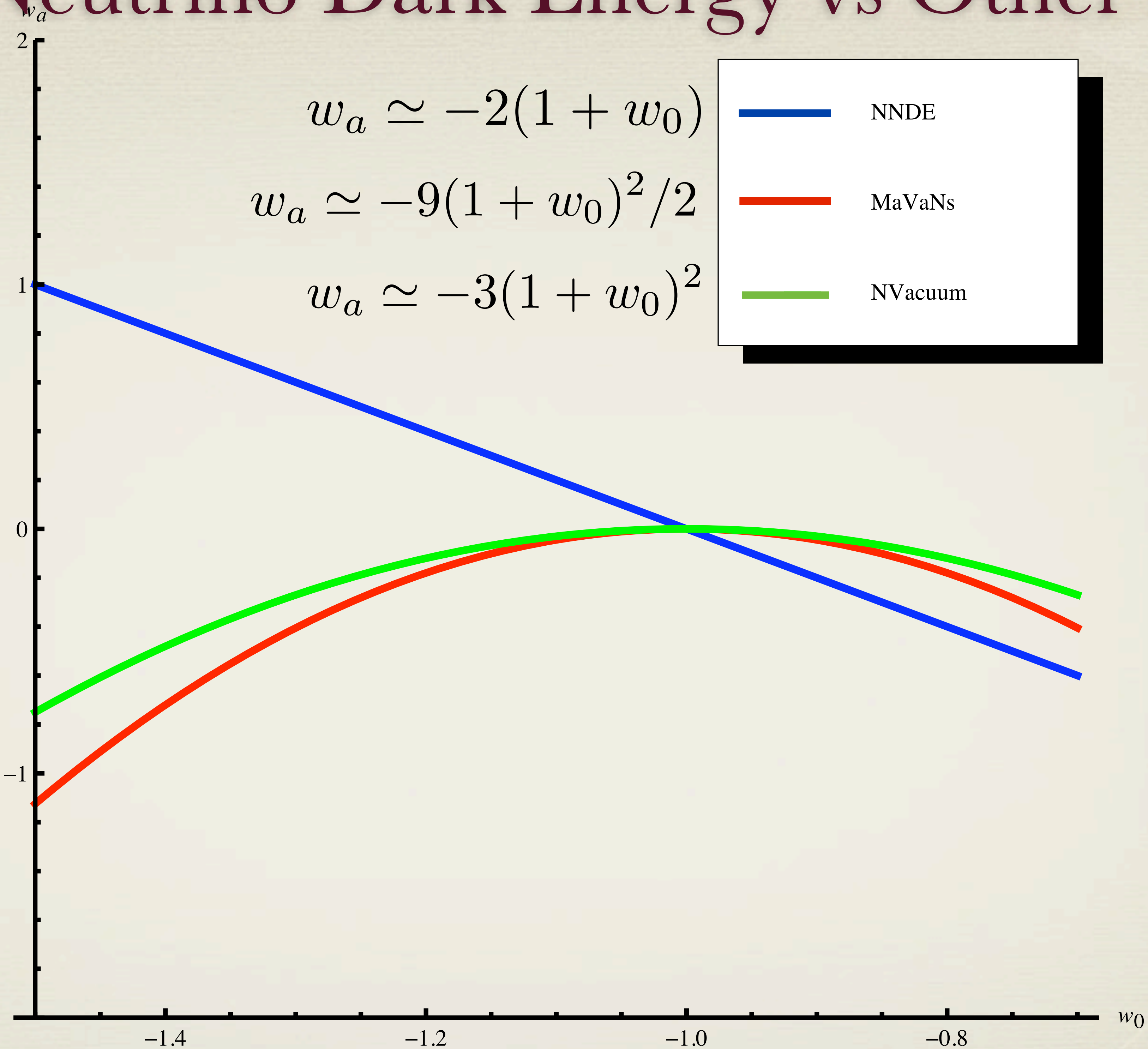


Although there is no clear conclusion from todays data - there is room for optimism!

Natural Neutrino Dark Energy vs Other models



Natural Neutrino Dark Energy vs Other models

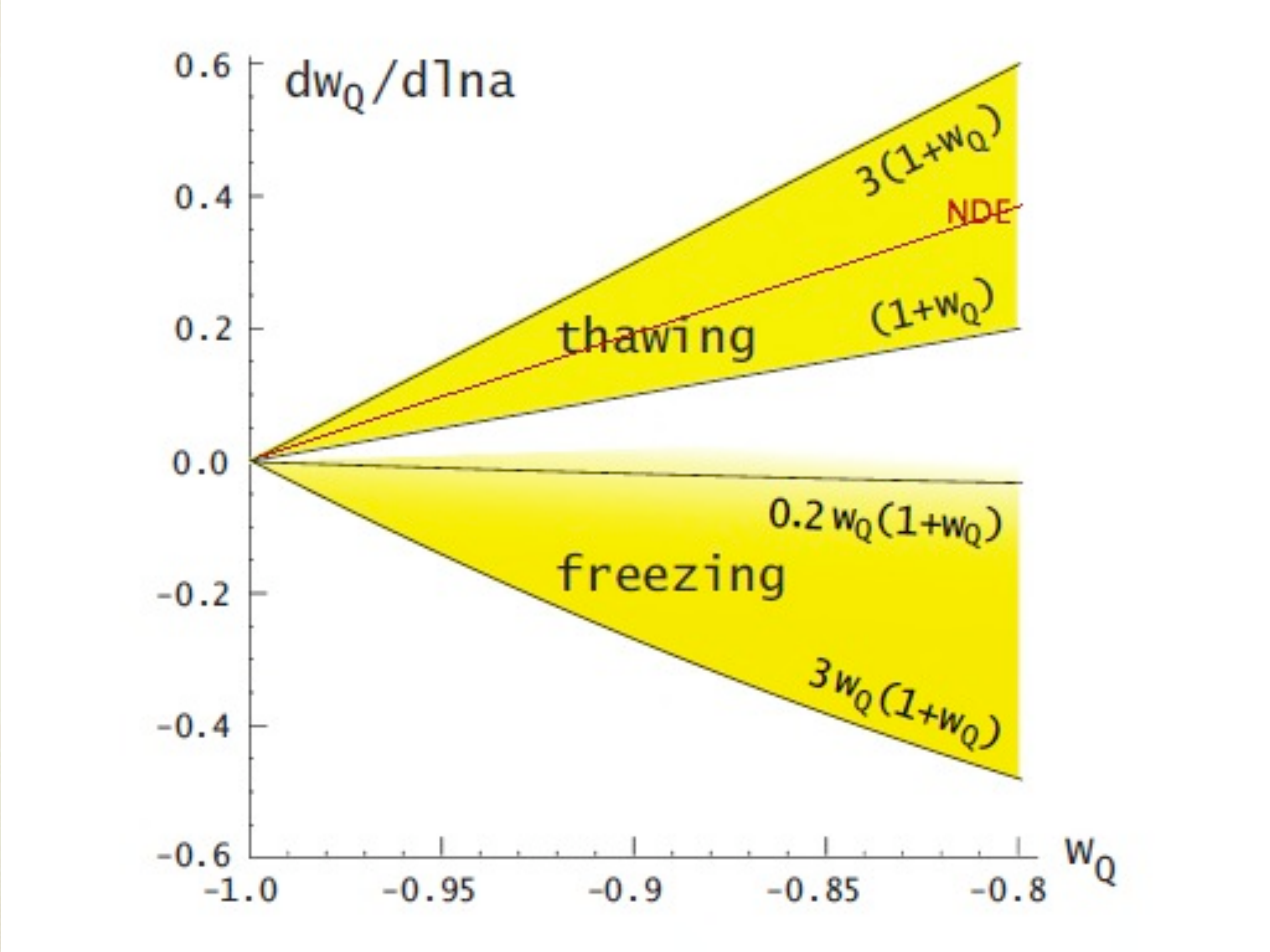


For the most general model:

$$w_a = -(1+w_0)\left(1+3(1+w_0)+\frac{a\frac{\partial}{\partial a}\left(\frac{\partial\rho}{\partial a}\right)}{\frac{\partial\rho}{\partial a}}\right)$$

Natural Neutrino Dark Energy vs Quintessence

from R. Caldwell and M. Kamionkowski (2009)



Compared to thawing and freezing quintessence scenarios, the neutrino dark energy is compatible with the thawing scenario. So how can we distinguish?

Future Data Analysis

Future Data Analysis

A more convenient notation for future data analysis

$$w = w_0 + w_1(1-a) + w_2(1-a)^2$$

Future Data Analysis

A more convenient notation for future data analysis

$$w = w_0 + w_1(1-a) + w_2(1-a)^2$$

The model predictions are

$$w_1 = -2(1 + w_0)$$

$$w_2 = 1 + w_0$$

Future Data Analysis

A more convenient notation for future data analysis

$$w = w_0 + w_1(1-a) + w_2(1-a)^2$$

The model predictions are

$$w_1 = -2(1+w_0)$$

$$w_2 = 1 + w_0$$

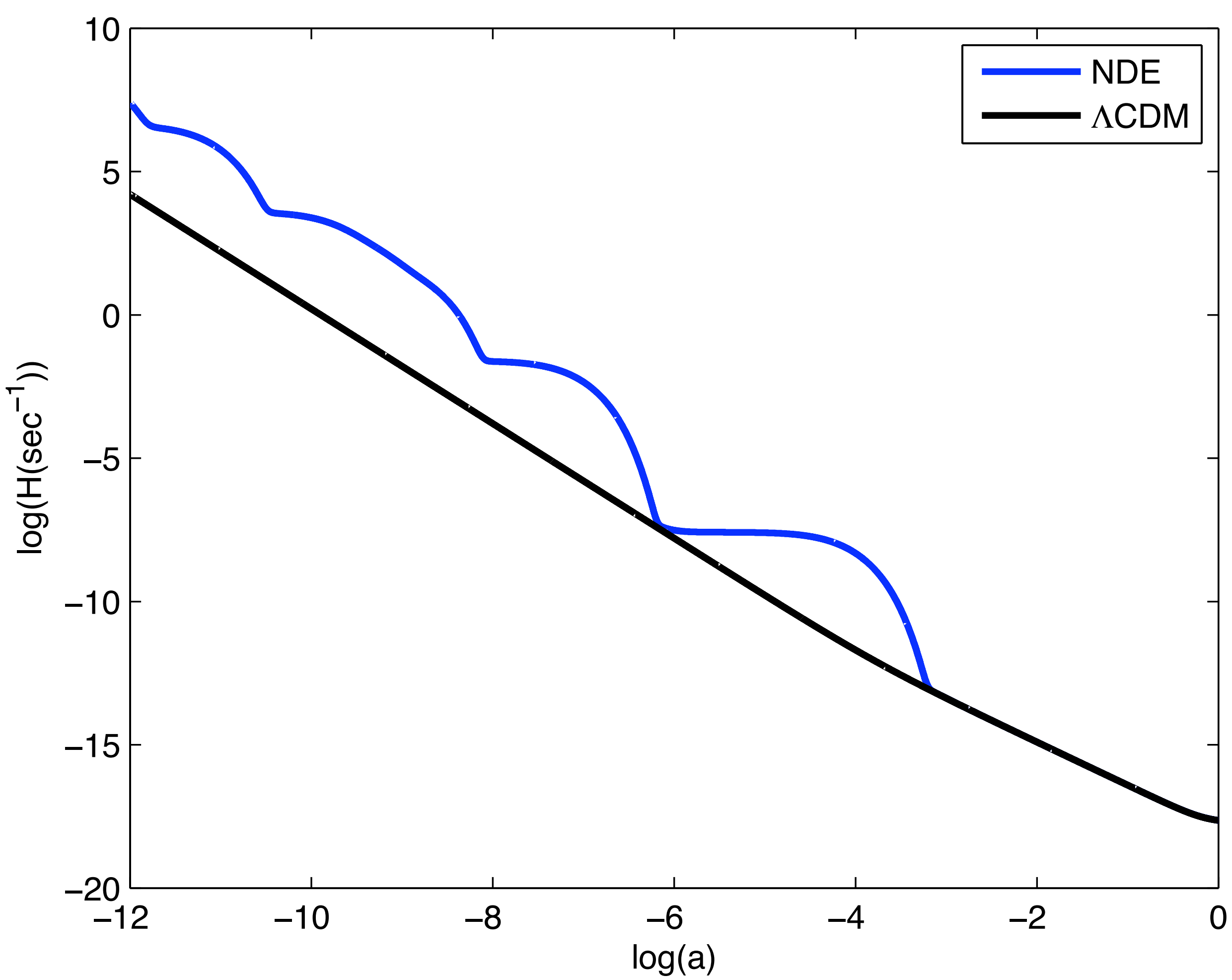
For present data this may represent too many parameters

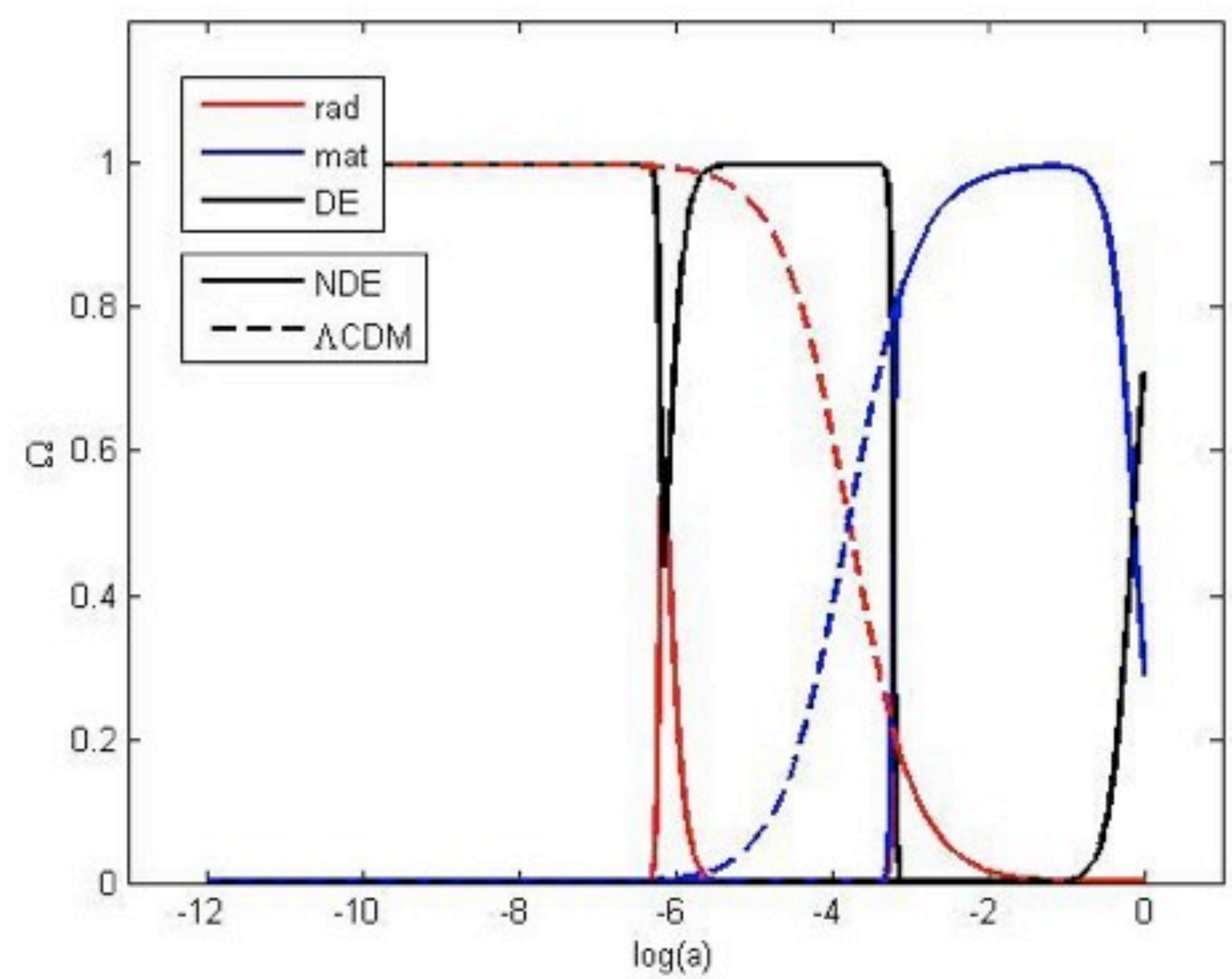
So a bias parameterization may be

$$w = w_0 + w_1\left[(1-a) - \frac{1}{2}(1-a)^2\right]$$

Natural Neutrino Dark Energy Cosmology

Another general prediction of this class of models is that at earlier stages of expansion, other particles were relativistic and contributed to the dark-energy $\sim m^4$.

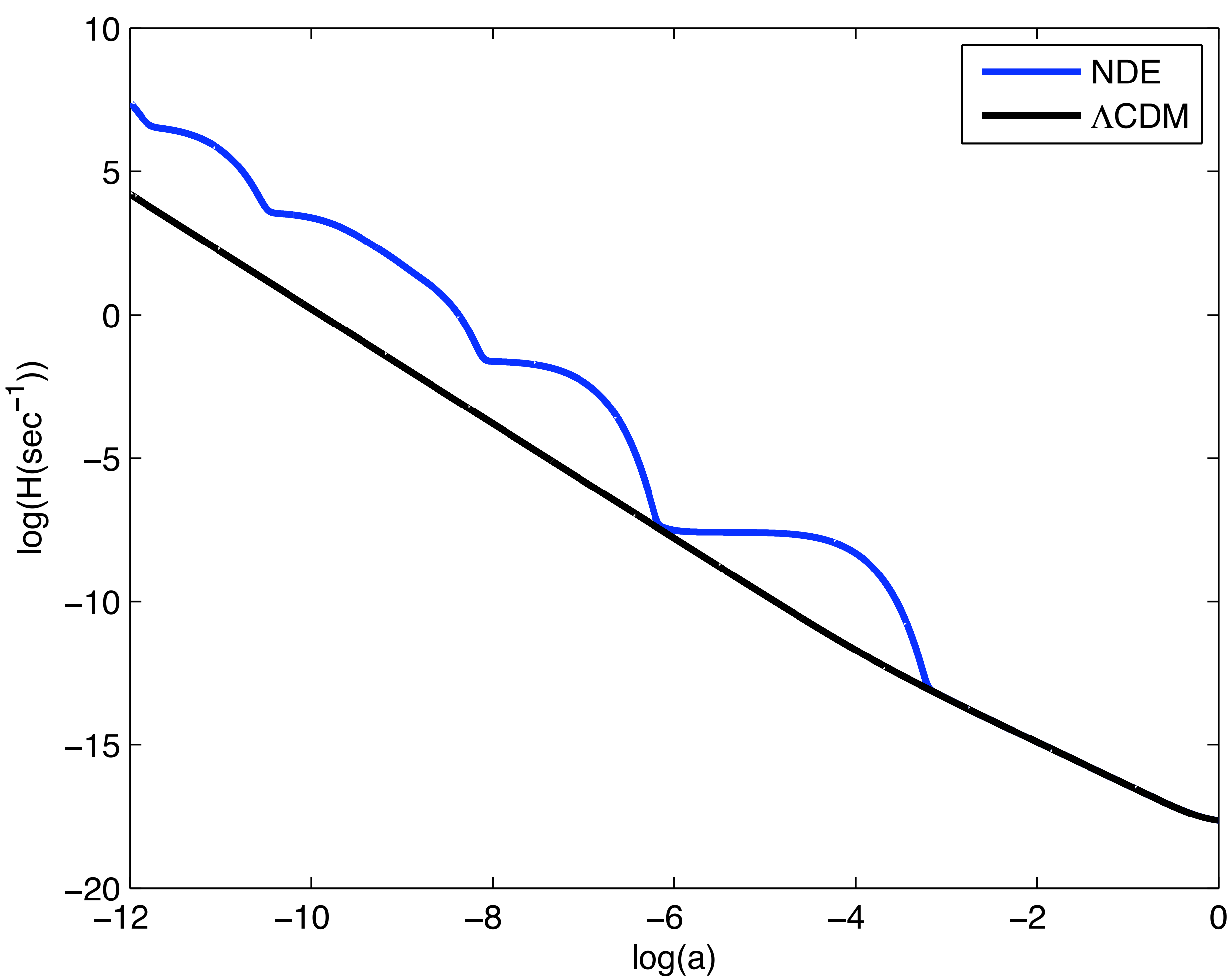


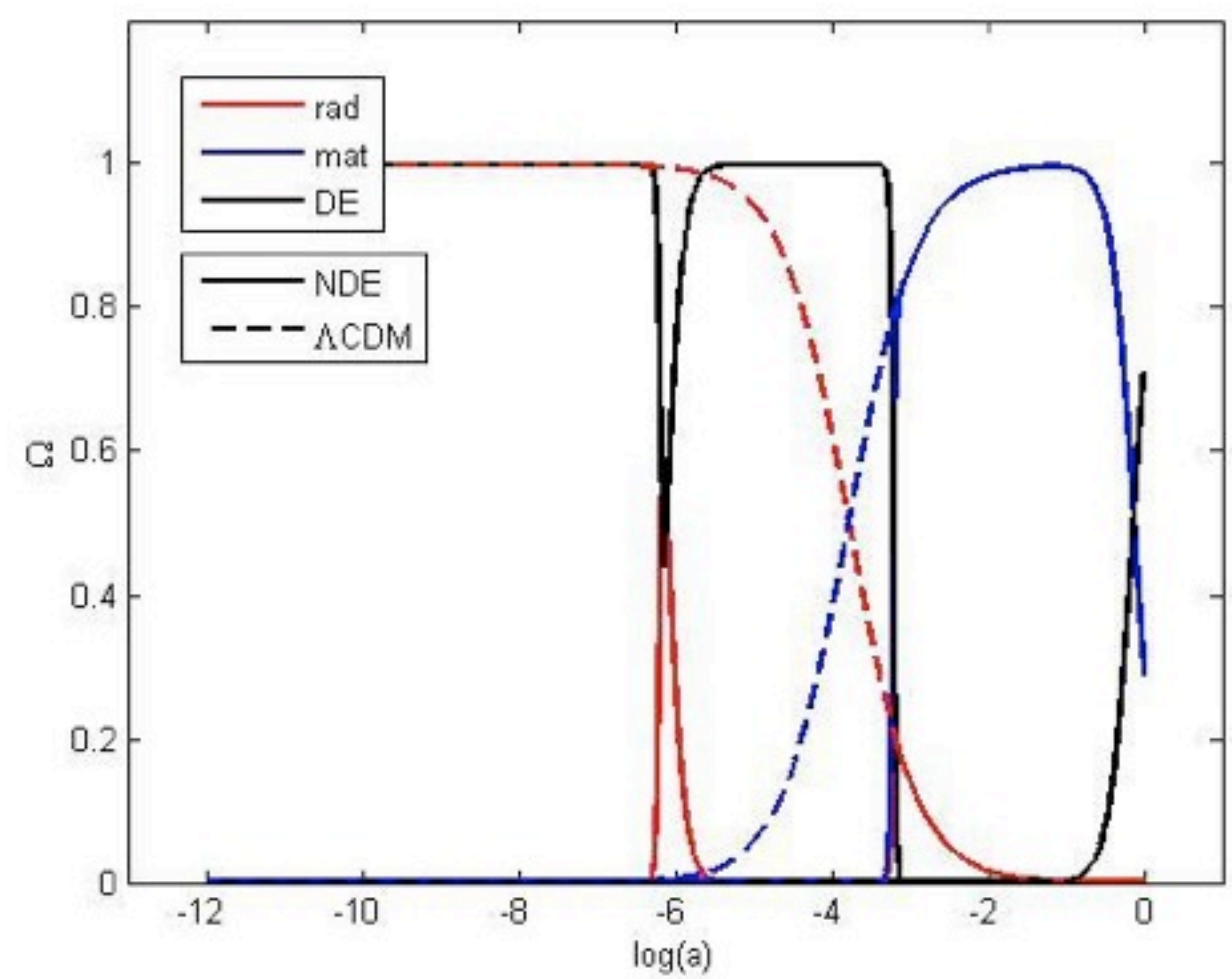


Natural Neutrino Dark Energy Cosmology

Another general prediction of this class of models is that at earlier stages of expansion, other particles were relativistic and contributed to the dark-energy $\sim m^4$.

Which happens first?



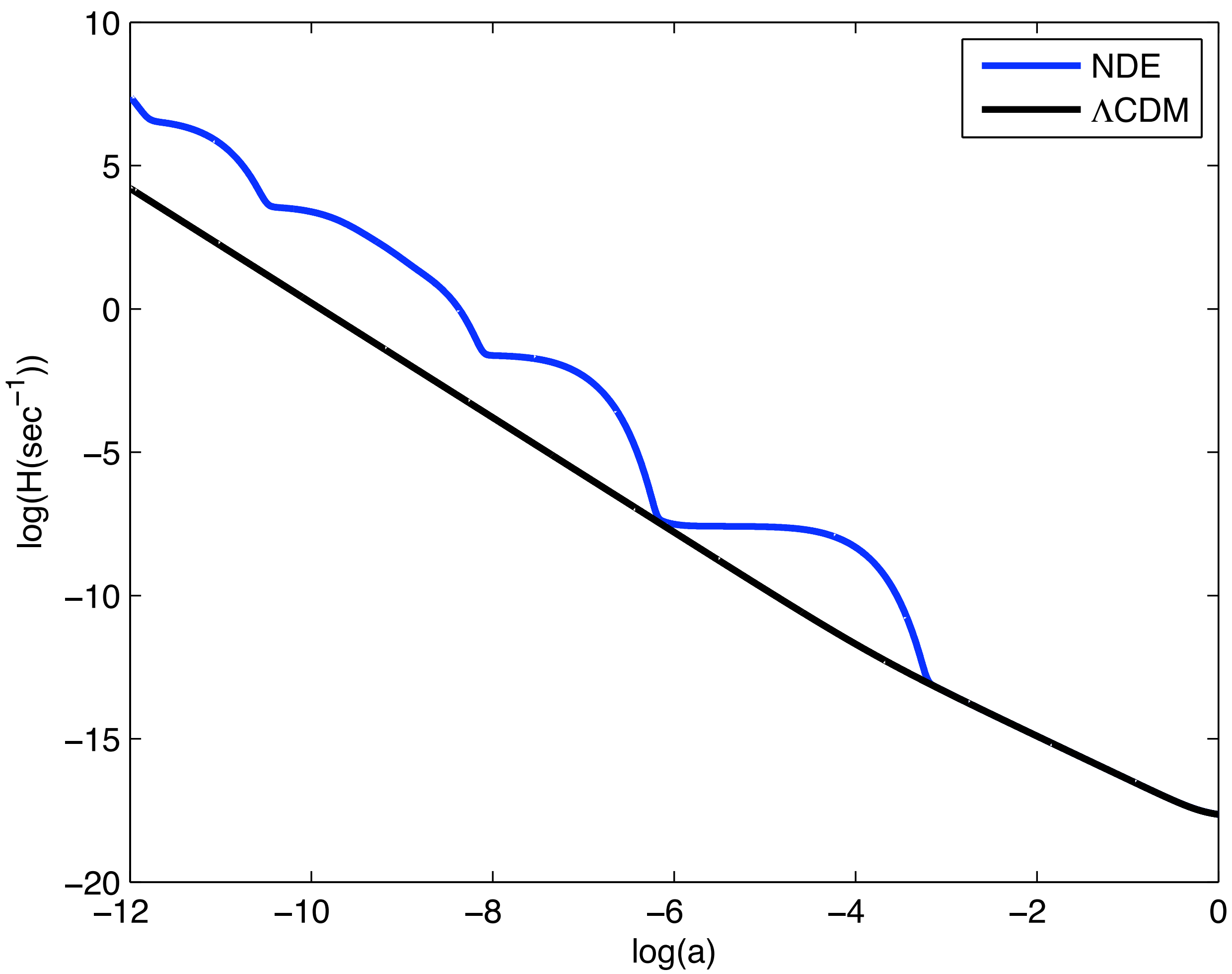


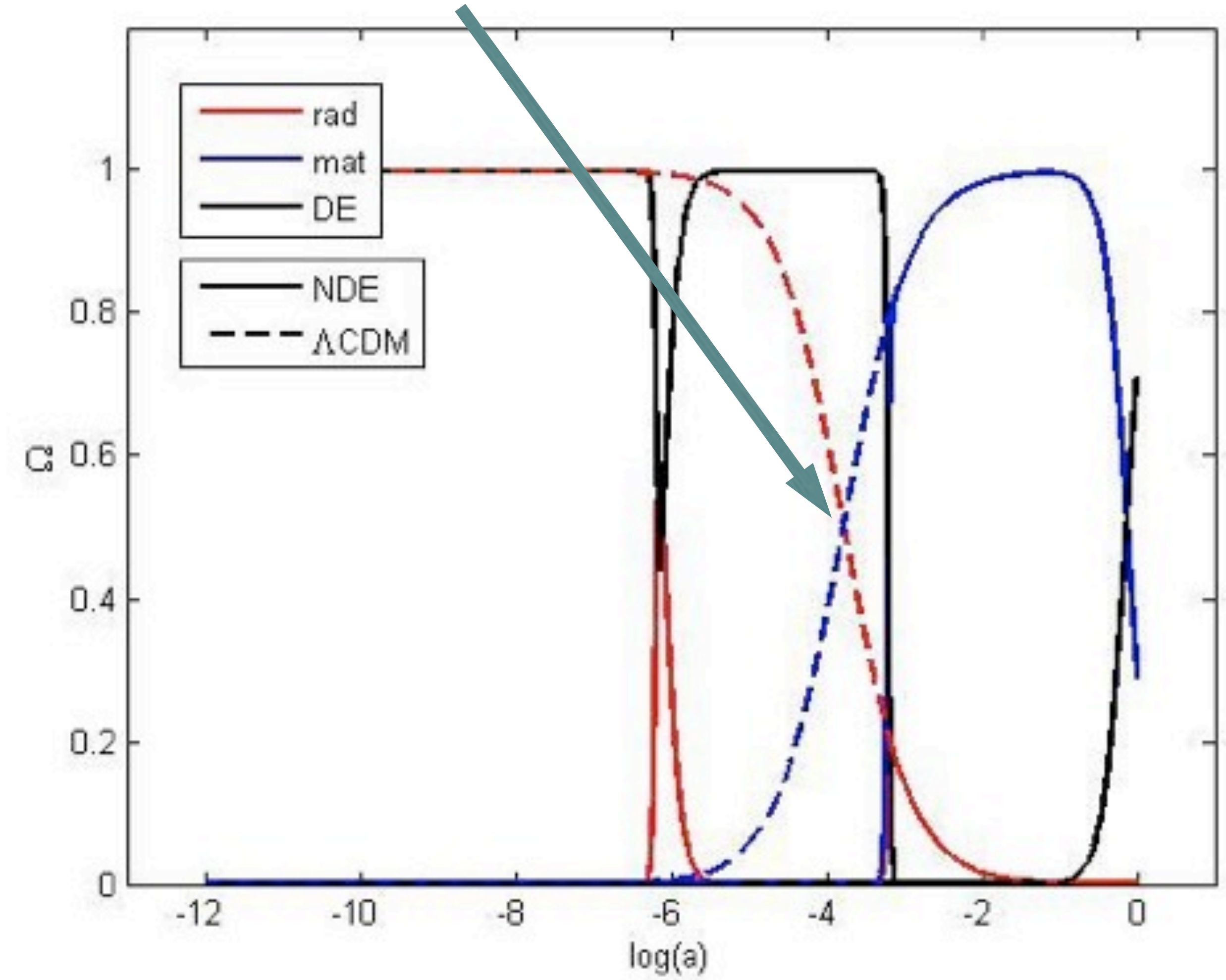
Natural Neutrino Dark Energy Cosmology

Another general prediction of this class of models is that at earlier stages of expansion, other particles were relativistic and contributed to the dark-energy $\sim m^4$.

Which happens first?

radiation-matter equality





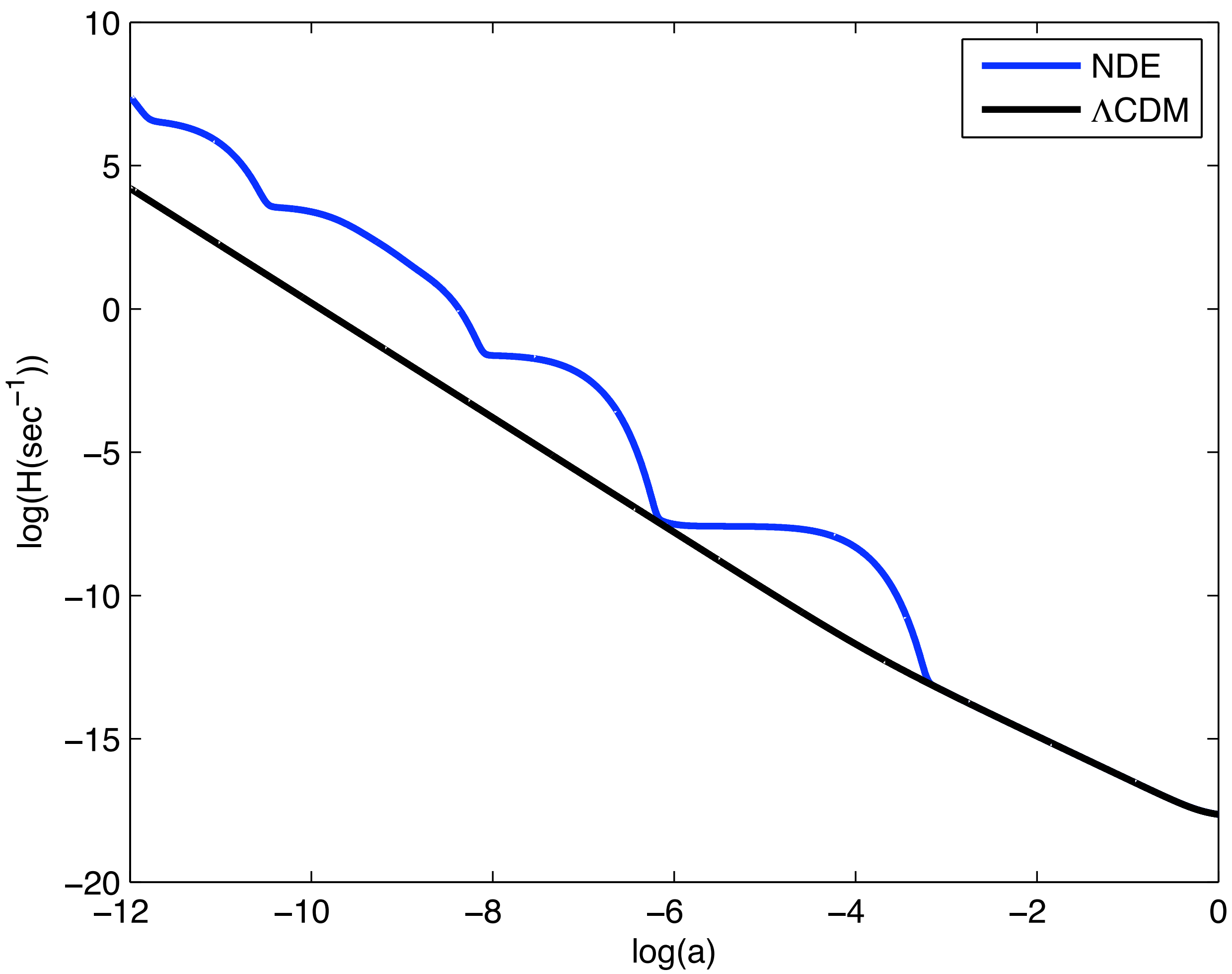
Natural Neutrino Dark Energy Cosmology

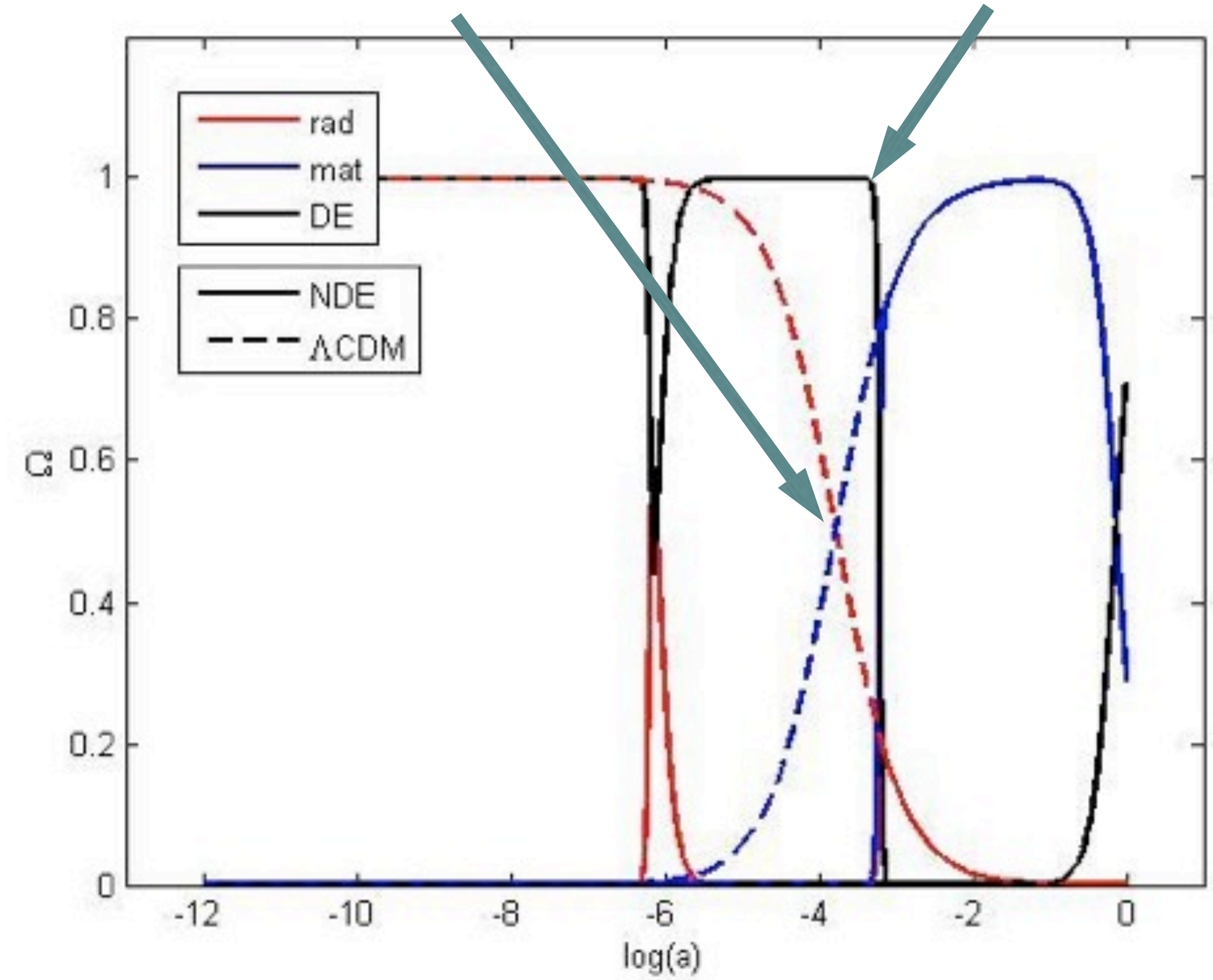
Another general prediction of this class of models is that at earlier stages of expansion, other particles were relativistic and contributed to the dark-energy $\sim m^4$.

Which happens first?

radiation-matter equality

dark energy domination





Natural Neutrino Dark Energy Cosmology

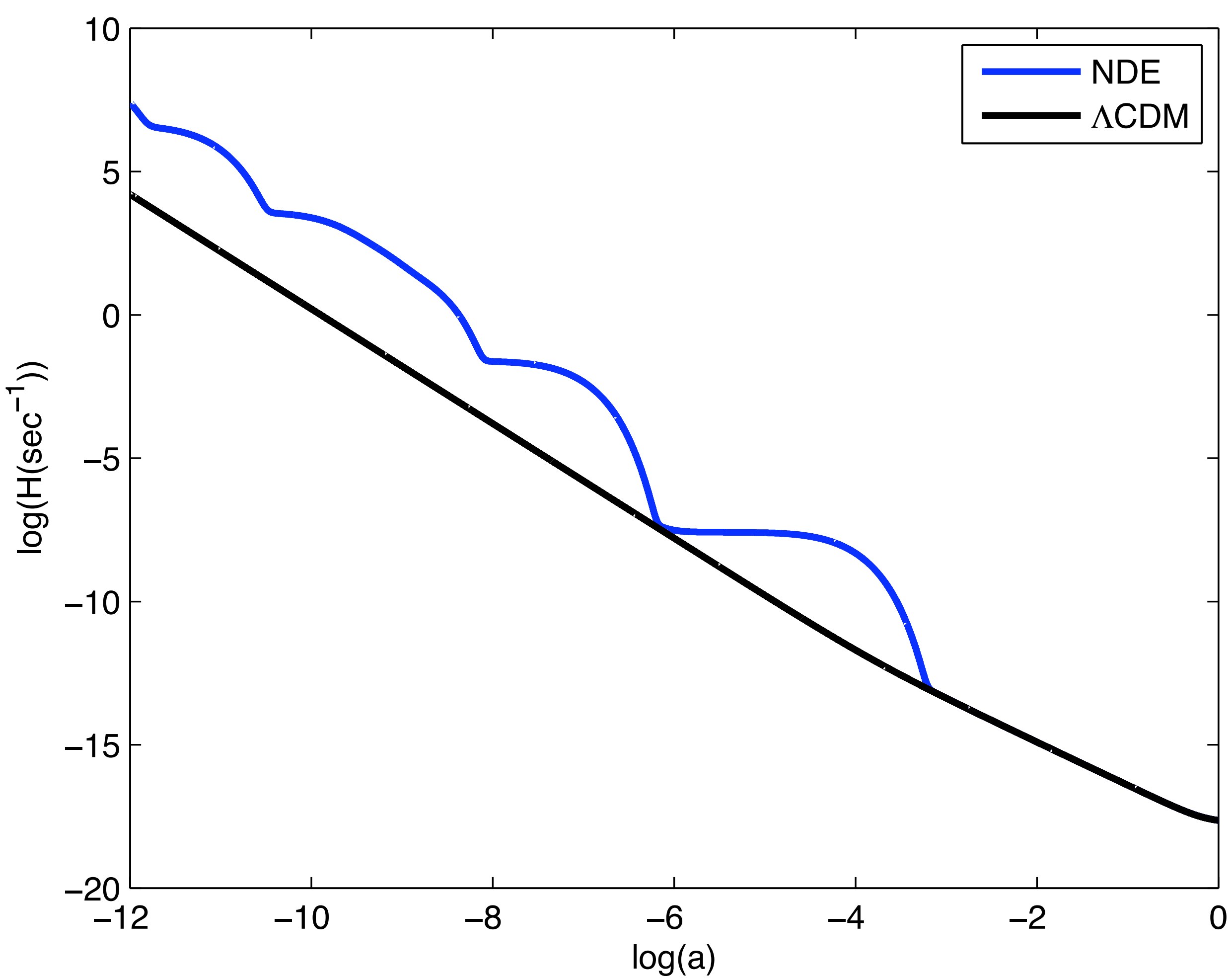
Another general prediction of this class of models is that at earlier stages of expansion, other particles were relativistic and contributed to the dark-energy $\sim m^4$.

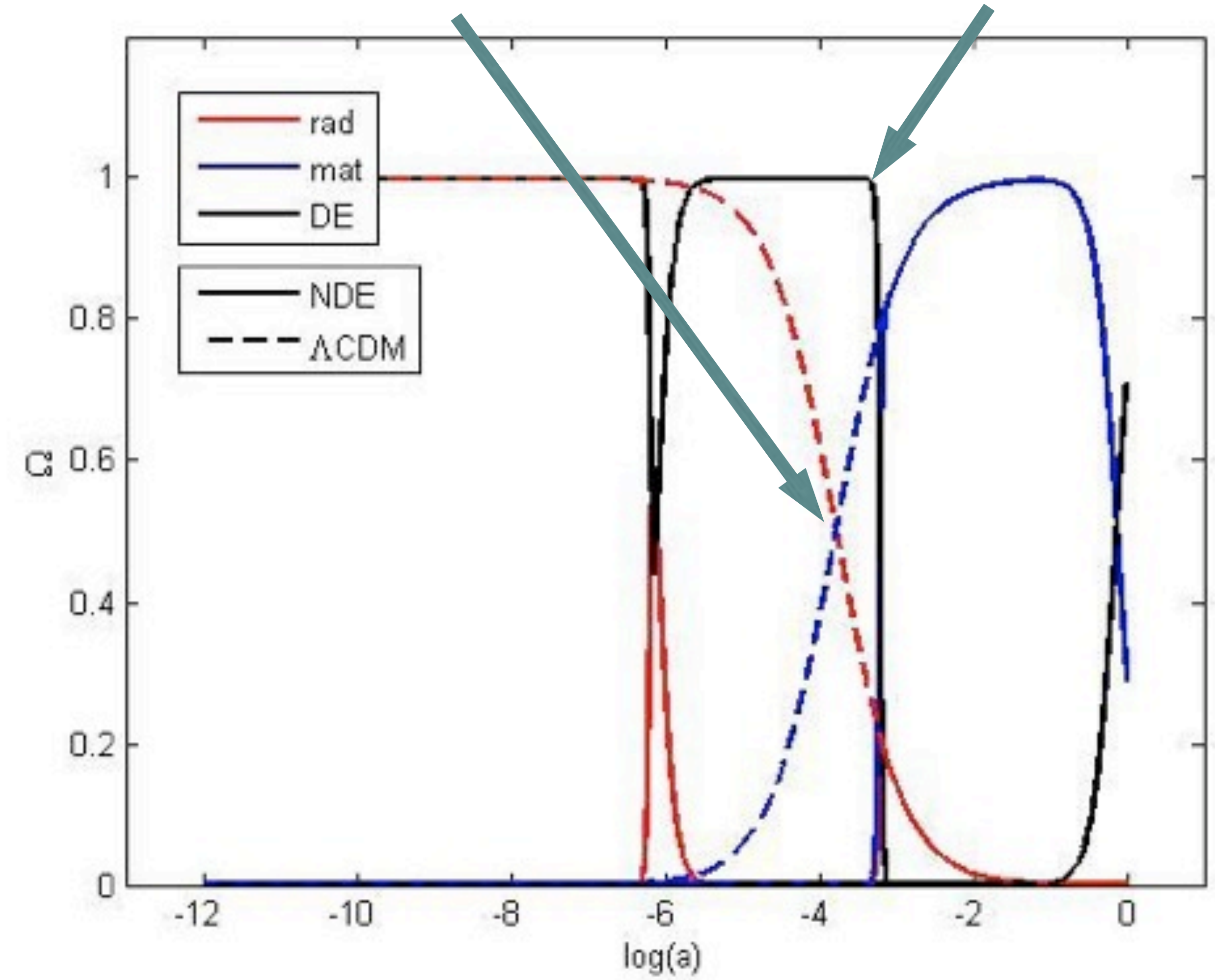
$m_{\nu_{\mu,\tau}} \sim T_{eq}$

Which happens first?

radiation-matter equality

dark energy domination





Natural Neutrino Dark Energy Cosmology

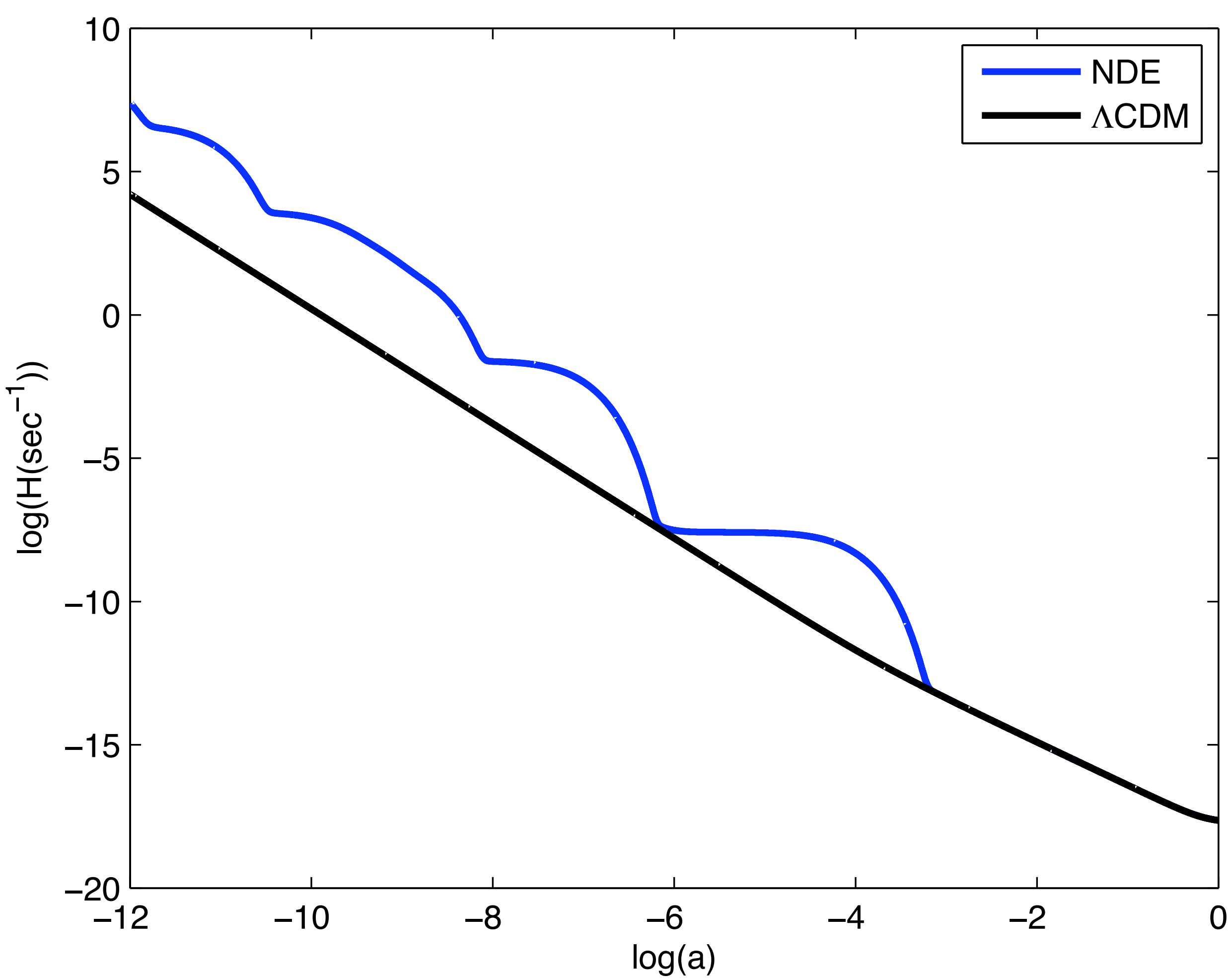
Another general prediction of this class of models is that at earlier stages of expansion, other particles were relativistic and contributed to the dark-energy $\sim m^4$.

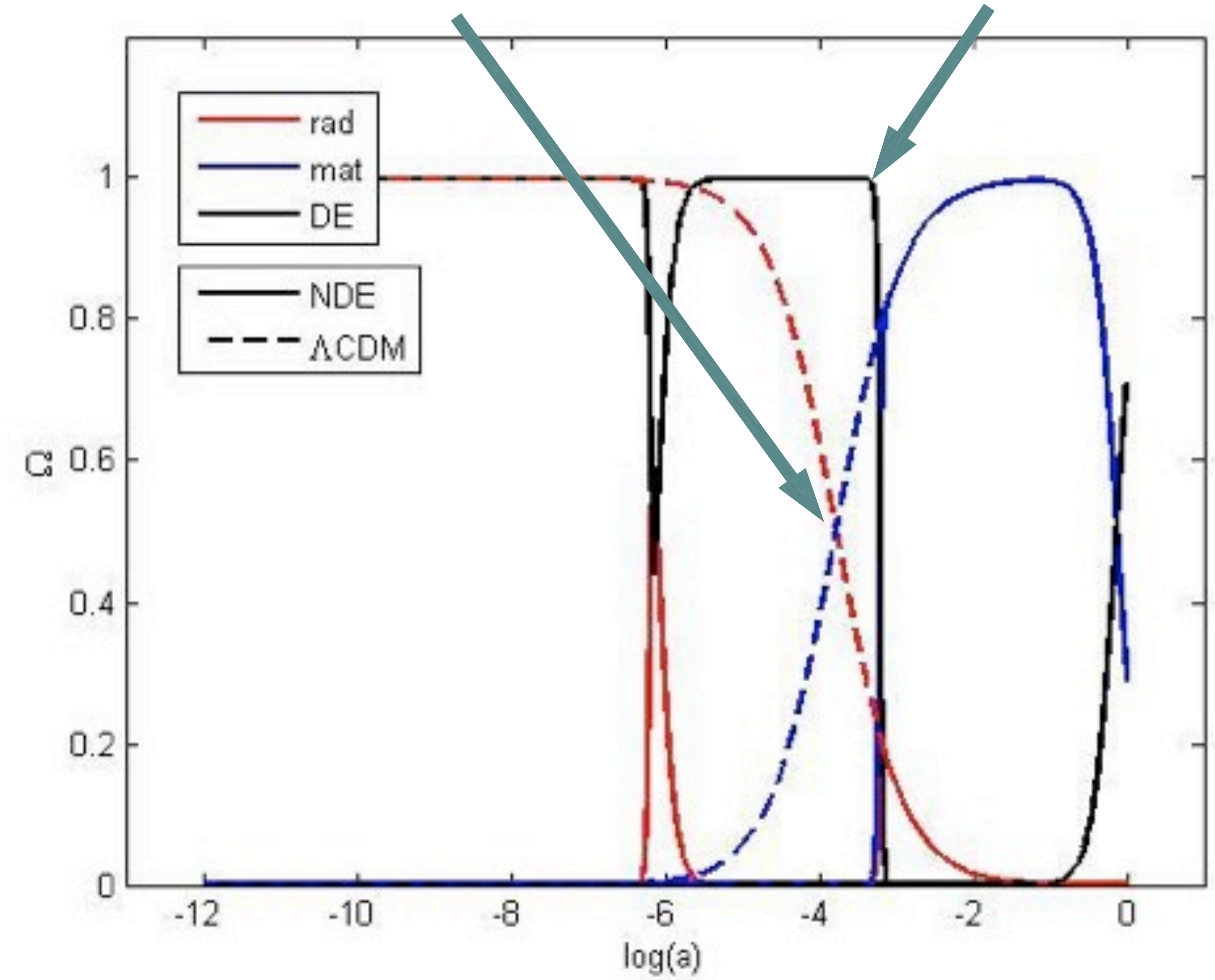
$m_{\nu_{\mu,\tau}} \sim T_{eq}$ →

Which happens first?

radiation-matter equality

dark energy domination





Natural Neutrino Dark Energy Cosmology

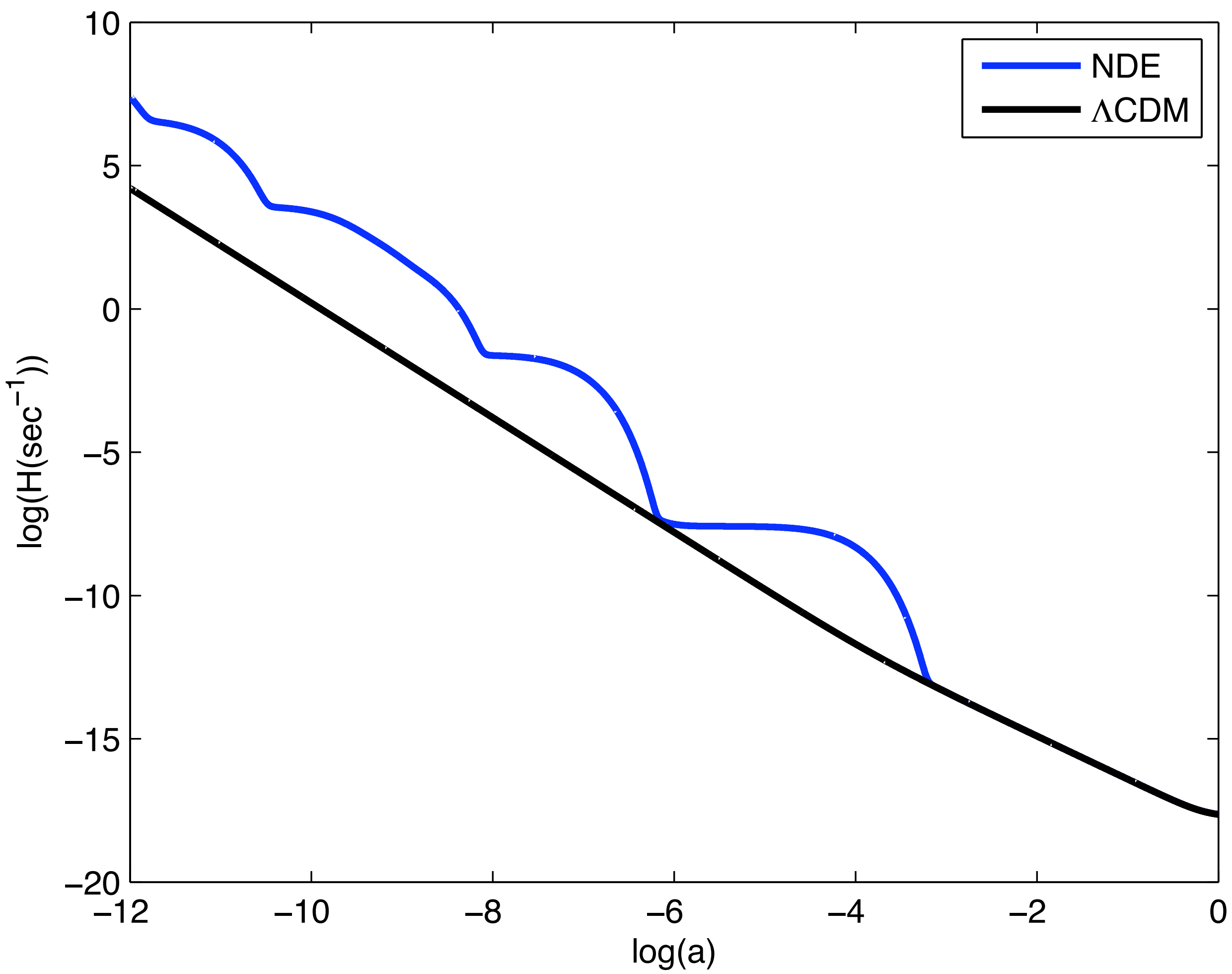
Another general prediction of this class of models is that at earlier stages of expansion, other particles were relativistic and contributed to the dark-energy $\sim m^4$.

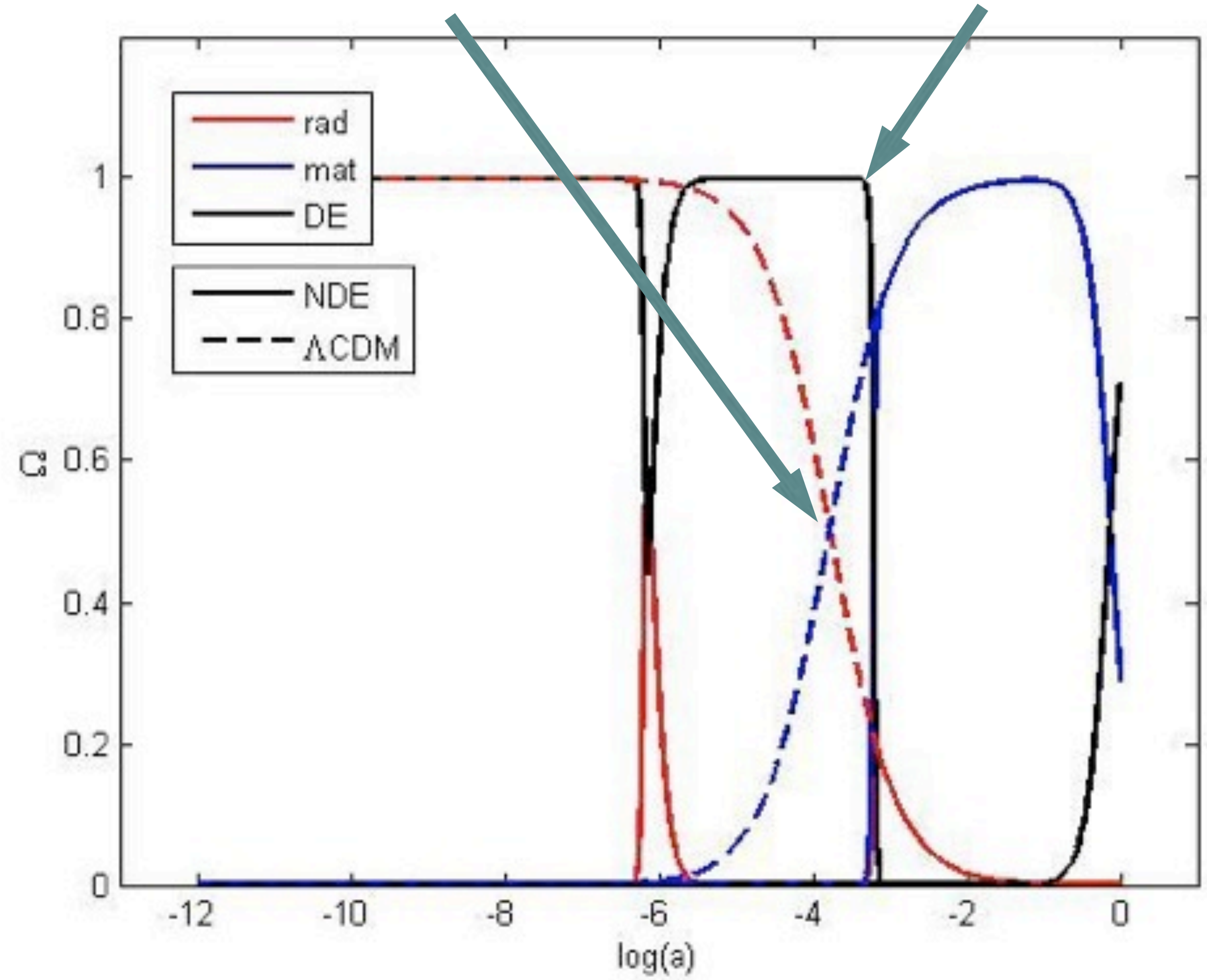
$m_{\nu_{\mu,\tau}} \sim T_{eq}$ ➡ A deviation from the standard structure formation, should be detected

Which happens first?

radiation-matter equality

dark energy domination





An Example Model

An Example Model

Vacuum fluctuations usually result in energy density

$$\delta\rho = Cm^4 \ln(\Lambda_{cutoff}/m)$$

An Example Model

Vacuum fluctuations usually result in energy density

$$\delta\rho = Cm^4 \ln(\Lambda_{cutoff}/m)$$

Casimir modes of the vacuum are evanescent.
Thus a mode with energy E will decay as

$$\exp(-Ex)$$

An Example Model

Vacuum fluctuations usually result in energy density

$$\delta\rho = Cm^4 \ln(\Lambda_{cutoff}/m)$$

Casimir modes of the vacuum are evanescent.
Thus a mode with energy E will decay as

$$\exp(-Ex)$$

Thus, as an example, we will study a model with:

$$\rho_{DE} = Cm_\nu^4 \ln(M_{Plank}/m_\nu) \exp(-E_\nu l_\nu)$$

An Example Model

Vacuum fluctuations usually result in energy density

$$\delta\rho = Cm^4 \ln(\Lambda_{cutoff}/m)$$

Casimir modes of the vacuum are evanescent.
Thus a mode with energy E will decay as

$$\exp(-Ex)$$

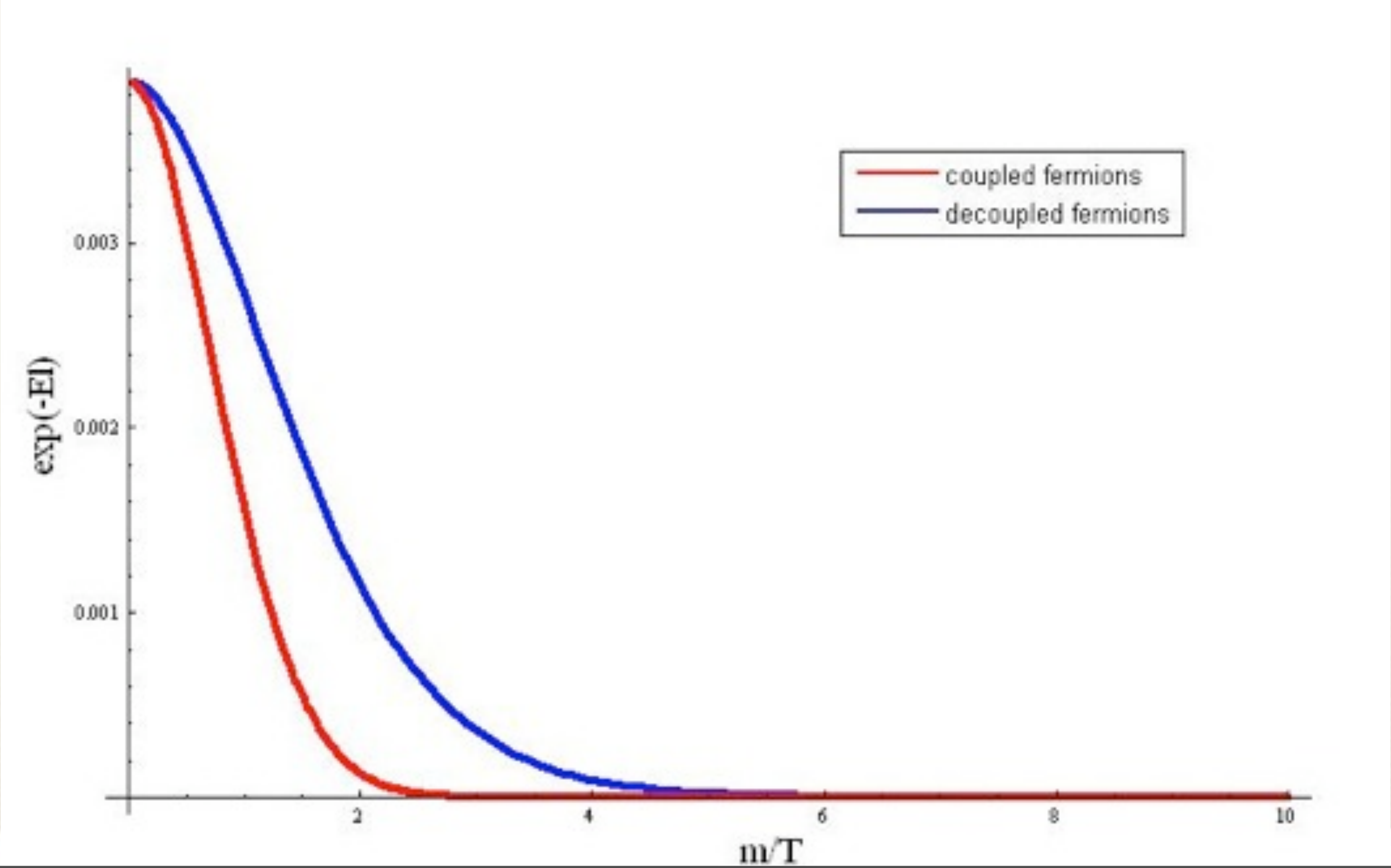
Thus, as an example, we will study a model with:

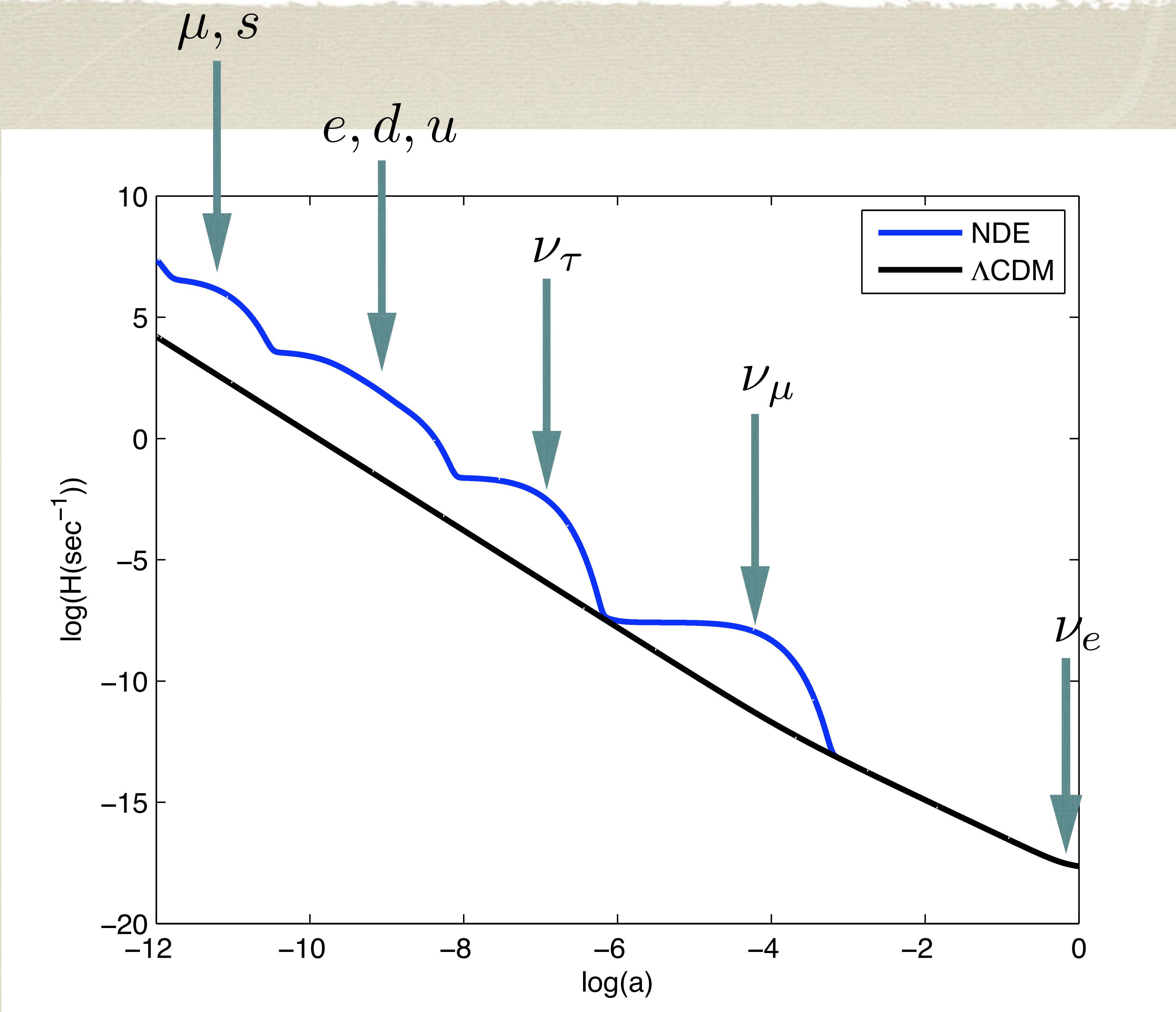
$$\rho_{DE} = Cm_\nu^4 \ln(M_{Plank}/m_\nu)\exp(-E_\nu l_\nu)$$

$$1 + w_{DE} \simeq \left(\frac{m_\nu}{3.76 \cdot 10^{-4} eV}\right)^2$$

Coupled vs Decoupled

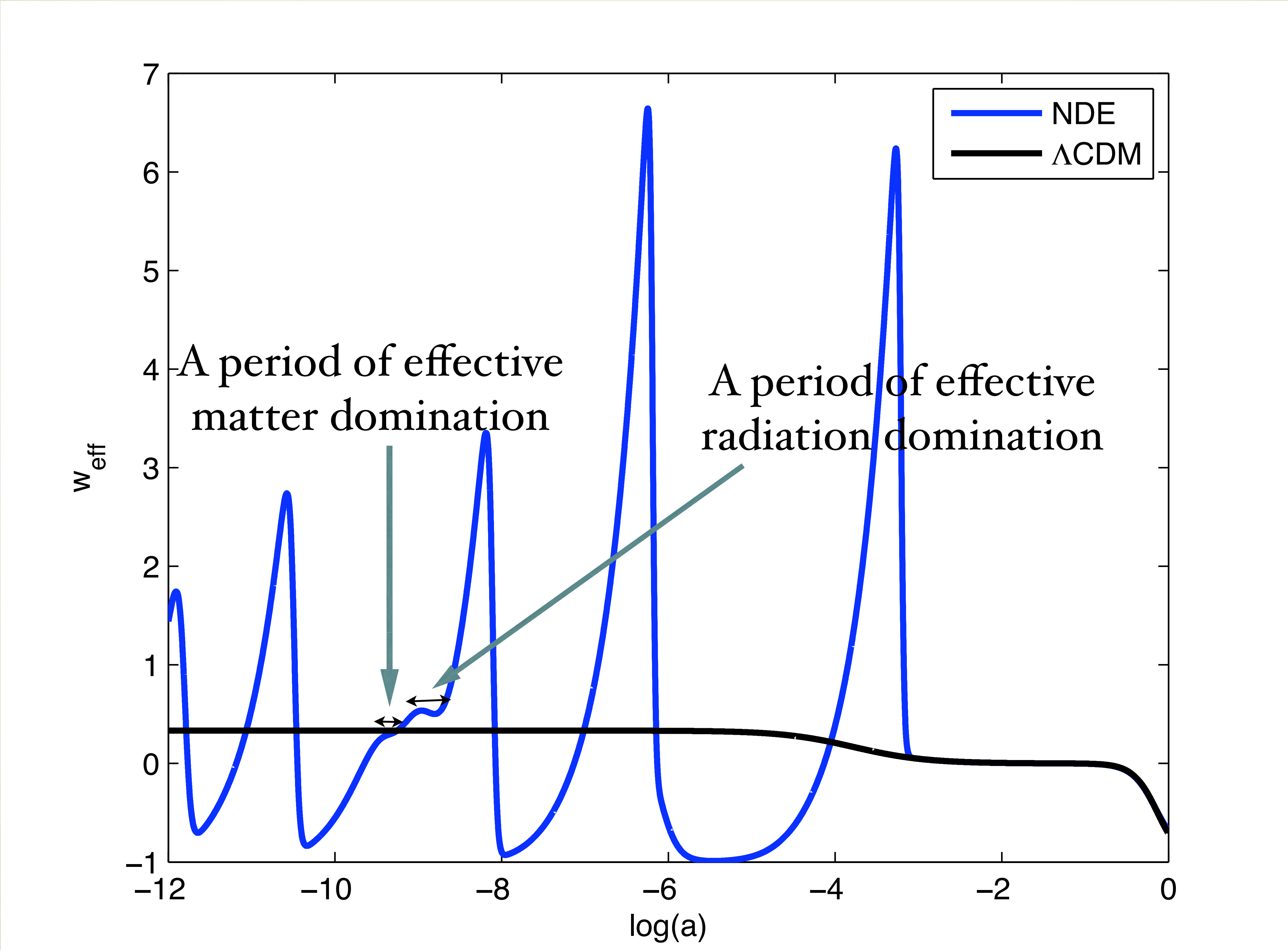
Decoupled (assuming decoupling temperature >> m)	Coupled
$n = 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{1}{1+\exp(p/T)}$	$n = 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{1}{1+\exp(\sqrt{p^2+m^2}/T)}$
$\rho = 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{\sqrt{p^2+m^2}}{1+\exp(p/T)}$	$\rho = 2\int_0^\infty \frac{4\pi p^2 dp}{(2\pi)^3}\frac{\sqrt{p^2+m^2}}{1+\exp(\sqrt{p^2+m^2}/T)}$





The neutrino and quark masses used in the plot are speculative

Fermion mass hierarchy generates a long period of dark energy domination. However because some of the fermion masses are of the same order of magnitude, DE domination does not imply necessarily that $w_{eff} \simeq -1$.



Open Questions for Future Research

For the general class of models

Open Questions for Future Research

For the general class of models

* The effects of past dark energy domination on the CMB. Can this lead to constraints on heavier neutrino masses?

Open Questions for Future Research

<u>For the general class of models</u>

* The effects of past dark energy domination on the CMB. Can this lead to constraints on heavier neutrino masses?
* The effects of past dark energy domination on structure formation.

Open Questions for Future Research

For the general class of models

* The effects of past dark energy domination on the CMB. Can this lead to constraints on heavier neutrino masses?
* The effects of past dark energy domination on structure formation.
* The effects of past dark energy domination on BBN.

Open Questions for Future Research

For the general class of models

* The effects of past dark energy domination on the CMB. Can this lead to constraints on heavier neutrino masses?
* The effects of past dark energy domination on structure formation.
* The effects of past dark energy domination on BBN.
* Since dark energy domination leads to inflationary expansion, it may have an effect on inflationary constraints. Can such an effect be measured?

Open Questions for Future Research

For the general class of models

* The effects of past dark energy domination on the CMB. Can this lead to constraints on heavier neutrino masses?
* The effects of past dark energy domination on structure formation.
* The effects of past dark energy domination on BBN.
* Since dark energy domination leads to inflationary expansion, it may have an effect on inflationary constraints. Can such an effect be measured?
* Will tighter dark energy constraints from future measurements, verify that $w_a = -2(1 + w_0)$?

Open Questions for Future Research

For the specific model

Open Questions for Future Research

For the specific model

* Precise measurement of neutrino masses using cosmology.

Open Questions for Future Research

For the specific model

* Precise measurement of neutrino masses using cosmology.
* Does neutrino non-homogeneity (clustering) effects the dark energy? Does it lead to non-homogeneity in dark energy?

Open Questions for Future Research

For the specific model

* Precise measurement of neutrino masses using cosmology.
* Does neutrino non-homogeneity (clustering) effects the dark energy? Does it lead to non-homogeneity in dark energy?
* Can the interactions that lead to dark energy be measured in the laboratory?

Conclusions

Conclusions

* Requiring that dark energy is generated from neutrino via a natural mechanism without exotic physics or new fields beyond the standard model, leads to some clear predictions regarding the behavior of dark energy.

Conclusions

- Requiring that dark energy is generated from neutrino via a natural mechanism without exotic physics or new fields beyond the standard model, leads to some clear predictions regarding the behavior of dark energy.
- If these predictions will be verified in the future, it will strongly support the conjecture that dark energy is related to neutrino (and fermions in general), even without a specific model.

Conclusions

* Requiring that dark energy is generated from neutrino via a natural mechanism without exotic physics or new fields beyond the standard model, leads to some clear predictions regarding the behavior of dark energy.
* If these predictions will be verified in the future, it will strongly support the conjecture that dark energy is related to neutrino (and fermions in general), even without a specific model.
* A model following the above guidelines was presented.

Conclusions

* Requiring that dark energy is generated from neutrino via a natural mechanism without exotic physics or new fields beyond the standard model, leads to some clear predictions regarding the behavior of dark energy.
* If these predictions will be verified in the future, it will strongly support the conjecture that dark energy is related to neutrino (and fermions in general), even without a specific model.
* A model following the above guidelines was presented.
* Many intriguing questions for future research follow from this work.

THANK YOU
FOR YOUR ATTENTION