Sterile neutrino oscillations with altered dispersion relations in Cosmology and Astrophysics

Elke Aeikens

University Vienna

17th November 2015

Seminar on particle physics

Faculty of Physics

Outline

- **Introduction**: Oscillations with sterile neutrinos with altered dispersion relations (ADR)
- **Astrophysics**: Sterile mixing in astrophysical neutrinos from IceCube
- **Cosmology**: Big Bang Nucleosynthesis as a test of new neutrino physics

Nobel price for discover **neutrino oscillations**

- Flavor- (ν_α) and mass eigenstates (ν_i) differ via an oscillation matrix U:

$$\nu_\alpha \neq \nu_i \quad \rightarrow \quad \nu_\alpha = U_{\alpha i}\,\nu_i \qquad \alpha, \beta \in \{e, \mu, \tau, s\}$$

There are different models for **neutrino mass**:

$$\begin{aligned} \mathcal{L}_M &\stackrel{?}{=} \mathcal{L}_{dirac} + \mathcal{L}_{majorana} \\ &\sim \nu_\alpha M \nu_\beta = \nu_i \underbrace{U^\dagger M\, U}_{m_{diag}} \nu_j \end{aligned}$$

What is the advantage of right handed/sterile neutrino oscillation?

Advantage of sterile Neutrinos

- **explain mass hierarchy** in right-handed neutrino mass models via the Seesaw mechanism. $[\mathrm{m}_{\nu_s} \gtrsim \mathrm{TeV}]$
(with additional higgs doublets...)
- **Dark matter candidates** $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_s} \lesssim \mathrm{TeV}]$
- **Baryon asymmetry** via Leptogenesis in νMSM models $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_s} \lesssim \mathrm{GeV}]$
- **Detected anomalies** at: LSND, MiniBooNE, gallium detectors: GALLEX, SAGE, reactor experiments... $[\mathrm{m}_{\nu_s} \sim \mathrm{eV}]$
(u.a here also: IceCube)

tightest constrains from cosmology:

- **Boundaries from BBN** (discussed here)
- **CMB measurement** from PLANCK sets limits on N_ν and also the **Large Scale Structure**.

Advantage of sterile Neutrinos

- **explain mass hierarchy** in right-handed neutrino mass models via the Seesaw mechanism. $[\mathrm{m}_{\nu_s} \gtrsim \mathrm{TeV}]$
  (with additional higgs doublets...)
  actual work
- **Dark matter candidates** $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_s} \lesssim \mathrm{TeV}]$
- **Baryon asymmetry** via Leptogenesis in νMSM models $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_s} \lesssim \mathrm{GeV}]$
- **Detected anomalies** at: LSND, MiniBooNE, gallium detectors: GALLEX, SAGE, reactor experiments... $[\mathrm{m}_{\nu_s} \sim \mathrm{eV}]$
  (u.a here also: IceCube)

tightest constrains from cosmology:

- **Boundaries from BBN** (discussed here)
- **CMB measurement** from PLANCK sets limits on N_ν and also the **Large Scale Structure**.

Advantage of sterile Neutrinos

- **explain mass hierarchy** in right-handed neutrino mass models via the Seesaw mechanism. $[\mathrm{m}_{\nu_s} \gtrsim \mathrm{TeV}]$
(with additional higgs doublets...)

actual work

- **Dark matter candidates** $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_s} \lesssim \mathrm{TeV}]$
- **Baryon asymmetry** via Leptogenesis in νMSM models $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_s} \lesssim \mathrm{GeV}]$
- **Detected anomalies** at: LSND, MiniBooNE, gallium detectors: GALLEX, SAGE, reactor experiments... $[\mathrm{m}_{\nu_s} \sim \mathrm{eV}]$
(u.a here also: IceCube)

tightest constrains from cosmology:

- **Boundaries from BBN** (discussed here)

previous work

- **CMB measurement** from PLANCK sets limits on N_ν and also the **Large Scale Structure**.

Oscillations with sterile neutrinos

In vacuum:

2-flavor-mixing approximation, $\nu_l \leftrightarrow \nu_s$ ($l \in \{e, \mu, \tau\}$)

equation of motion for a particle

$$\frac{d}{dt}|\nu_\beta(t)\rangle = \underbrace{\sum_j U_{\beta j} H^M_{jj} U_{\alpha j}}_{\frac{\Delta m^2}{4E}\begin{pmatrix} -c(2\theta) & s(2\theta) \\ s(2\theta) & c(2\theta) \end{pmatrix}} |\nu_\alpha\rangle$$

mixing matrix

$$U_{\alpha j} = \begin{pmatrix} c\theta & s\theta \\ -s\theta & c\theta \end{pmatrix}$$

$$U^{\text{4fl.}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$\alpha, \beta \in \{l, s\}$

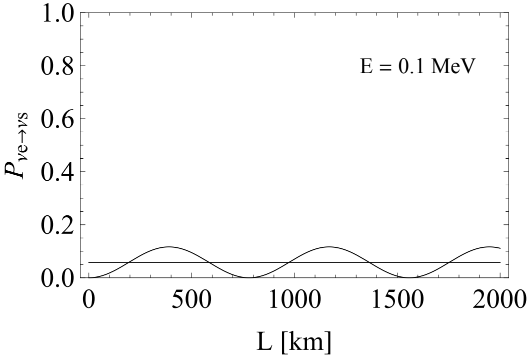
oscillation probability

$$P_{\nu_l \to \nu_s} = |\langle \nu_s | \nu_l(t) \rangle|^2$$

$$\langle P_{\nu_l \to \nu_s} \rangle = \sum_j |U_{lj}|^2 |U_{sj}|^2 = \langle \sin^2(\frac{\Delta m^2}{2E} x) \rangle \sin^2(2\theta) = \frac{1}{2} \sin^2(2\theta)$$

Oscillations with sterile neutrinos

In vacuum:



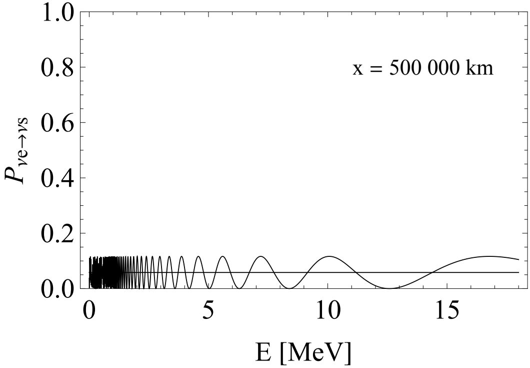
oscillation probability

$$P_{\nu_l \to \nu_s} = |\langle \nu_s | \nu_l(t) \rangle|^2$$

$$\langle P_{\nu_l \to \nu_s} \rangle = \sum_j |U_{lj}|^2 |U_{sj}|^2 = \langle \sin^2(\frac{\Delta m^2}{2E} x) \rangle \sin^2(2\theta) = \frac{1}{2} \sin^2(2\theta)$$

Oscillations with sterile neutrinos

In vacuum:

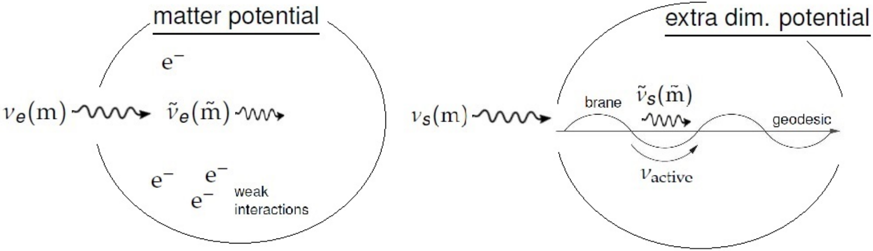


oscillation probability

$$P_{\nu_l \to \nu_s} = |\langle \nu_s | \nu_l(t) \rangle|^2$$

$$\langle P_{\nu_l \to \nu_s} \rangle = \sum_j |U_{lj}|^2 |U_{sj}|^2 = \langle \sin^2(\frac{\Delta m^2}{2E} x) \rangle \sin^2(2\theta) = \frac{1}{2} \sin^2(2\theta)$$

Neutrino potentials



$A_{\text{matter}} \sim n_e(x, E_\nu^3)$ $\qquad$ $A_{\text{extradim.}} \sim \epsilon(x)\, E_\nu$

Large extra dimension - ADD model [N. Arkani-Hamed, S. Dimopoulos, G. Dvali, 1998]

- invented to explain weakness of gravity relative to other forces (hierarchy problem)
- solve neutrino Anomalies with $\epsilon \gtrsim 10^{-16}$, [Paes et al., 2005] (shortcut parameter: $\epsilon \sim \frac{\delta t}{t}$)

In potentials $A(E)$ - with altered dispersion relations (ADR):

equation of motion for a particle

$$\frac{d}{dt}\,|\tilde{\nu}_\alpha(t)\rangle = \left[\frac{\Delta m^2}{4E}\begin{pmatrix} -c(2\theta) & s(2\theta) \\ s(2\theta) & c(2\theta)\end{pmatrix} + \frac{1}{2E}\begin{pmatrix} A & 0 \\ 0 & 0\end{pmatrix}\right]|\tilde{\nu}_\alpha\rangle$$

in **matter** or in theories with shortcuts in **extra dimensions**:

$$A(E) = \begin{cases} \sqrt{2}\,G_F\,n_e(E^3)\cdot A_\alpha E^2/M_W^2, & \text{matter (in BBN)} \qquad A_e \approx 55.\,,\ A_{\mu/\tau} \approx 15.3 \\ \epsilon E, & \text{extra dimensions} \end{cases}$$

[Paes et al. Phys. Rev. D 72, 095017 (2005)]

In potentials $A(E)$ - with altered dispersion relations (ADR):

equation of motion for a particle

$$\frac{d}{dt}|\tilde{\nu}_\alpha(t)\rangle = \left[\frac{\Delta m^2}{4E}\begin{pmatrix}-c(2\theta) & s(2\theta)\\ s(2\theta) & c(2\theta)\end{pmatrix} + \frac{1}{2E}\begin{pmatrix}A & 0\\ 0 & 0\end{pmatrix}\right]|\tilde{\nu}_\alpha\rangle$$

$$= \frac{\Delta\tilde{m}^2}{4E}\begin{pmatrix}-c(2\tilde{\theta}) & s(2\tilde{\theta})\\ s(2\tilde{\theta}) & c(2\tilde{\theta})\end{pmatrix}|\tilde{\nu}_\alpha\rangle, \qquad \tilde{U}_{\alpha j} = \begin{pmatrix} c\tilde{\theta} & s\tilde{\theta}\\ -s\tilde{\theta} & c\tilde{\theta}\end{pmatrix}$$

oscillation probability

$$\langle \tilde{P}_{\nu_l\to\nu_s}\rangle = \sum_j |\tilde{U}_{lj}|^2|\tilde{U}_{sj}|^2 = \frac{1}{2}\sin^2(2\tilde{\theta})$$

$$\sin^2(2\tilde{\theta}) = \frac{\sin^2(2\theta)}{\cos^2(2\theta)\left(\frac{E}{E_{res}}-1\right)^2 + \sin^2(2\theta)}, \quad E_{res} = \frac{\Delta m^2}{2A(E_{res})}\cos(2\theta)$$

in **matter** or in theories with shortcuts in **extra dimensions**:

$$A(E) = \begin{cases} \sqrt{2}\,G_F\,n_e(E^3)\cdot A_\alpha E^2/M_W^2, & \text{matter (in BBN)} \qquad A_e \approx 55.\,,\ A_{\mu/\tau} \approx 15.3 \\ \epsilon E, & \text{extra dimensions}\end{cases}$$

[Paes et al. Phys. Rev. D 72, 095017 (2005)]

In potentials $A(E)$ - with altered dispersion relations (ADR):

equation of motion for a particle

$$\frac{d}{dt}|\tilde{\nu}_\alpha(t)\rangle = \left[\frac{\Delta m^2}{4E}\begin{pmatrix}-c(2\theta) & s(2\theta)\\ s(2\theta) & c(2\theta)\end{pmatrix} + \frac{1}{2E}\begin{pmatrix}A & 0\\ 0 & 0\end{pmatrix}\right]|\tilde{\nu}_\alpha\rangle$$

$$= \frac{\Delta\tilde{m}^2}{4E}\begin{pmatrix}-c(2\tilde{\theta}) & s(2\tilde{\theta})\\ s(2\tilde{\theta}) & c(2\tilde{\theta})\end{pmatrix}|\tilde{\nu}_\alpha\rangle, \qquad \tilde{U}_{\alpha j} = \begin{pmatrix} c\tilde{\theta} & s\tilde{\theta}\\ -s\tilde{\theta} & c\tilde{\theta}\end{pmatrix}$$

oscillation probability

$$\langle\tilde{P}_{\nu_l\to\nu_s}\rangle = \sum_j |\tilde{U}_{lj}|^2|\tilde{U}_{sj}|^2 = \frac{1}{2}\sin^2(2\tilde{\theta})$$

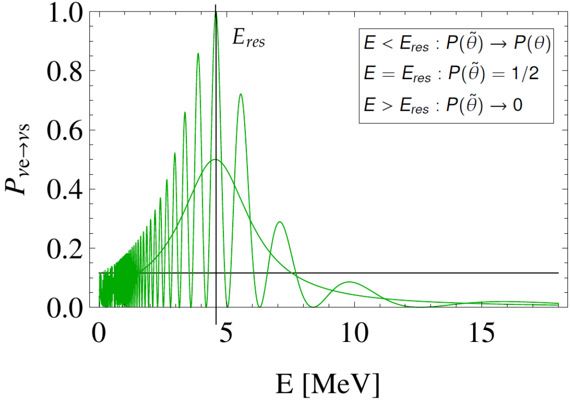
$$\sin^2(2\tilde{\theta}) = \frac{\sin^2(2\theta)}{\cos^2(2\theta)\left(\frac{E}{E_{res}}-1\right)^2 + \sin^2(2\theta)}, \quad E_{res} = \frac{\Delta m^2}{2A(E_{res})}\cos(2\theta)$$

in **matter** or in theories with shortcuts in **extra dimensions**:

$$A(E) = \begin{cases}\sqrt{2}\,G_F\,n_e(E^3)\cdot A_\alpha E^2/M_W^2, & \text{matter (in BBN)} \qquad A_e \approx 55.\,,\ A_{\mu/\tau} \approx 15.3\\ \epsilon E, & \text{extra dimensions}\end{cases}$$

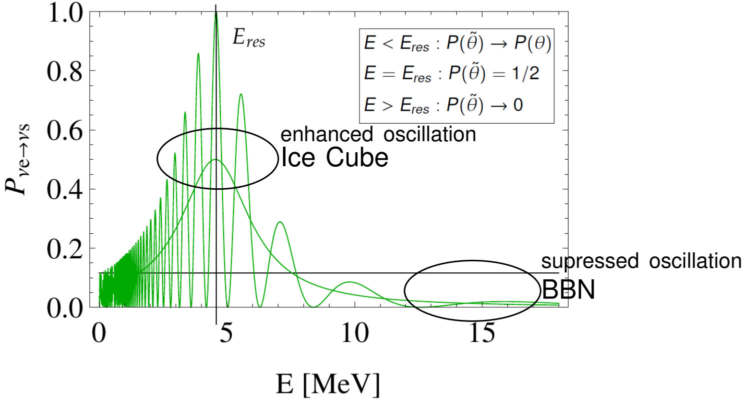
[Paes et al. Phys. Rev. D 72, 095017 (2005)]

In potentials $A(E)$ - with altered dispersion relations (ADR):



$$\sin^2(2\tilde{\theta}) = \frac{\sin^2(2\theta)}{\cos^2(2\theta)\left(\frac{E}{E_{res}} - 1\right)^2 + \sin^2(2\theta)}, \quad E_{res} = \frac{\Delta m^2}{2A(E_{res})}\cos(2\theta)$$

In potentials $A(E)$ - with altered dispersion relations (ADR):



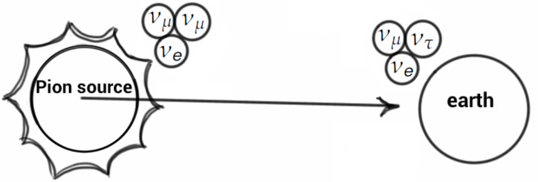
$$\sin^2(2\tilde{\theta}) = \frac{\sin^2(2\theta)}{\cos^2(2\theta)\left(\frac{E}{E_{res}} - 1\right)^2 + \sin^2(2\theta)}, \quad E_{res} = \frac{\Delta m^2}{2A(E_{res})}\cos(2\theta)$$

Astrophysical flavor ratios

High energetic, extragalactic neutrinos ($E_\nu \gtrsim$ TeV, PeV) give information about:

- extragalactic neutrino sources (Distance $\gtrsim$ Mpc / Mio ly)
- (non)standard mixing scenarios, e.g. with dark matter, ν_s with ADR

$$(\Phi^0_{\nu_e} : \Phi^0_{\nu_\mu} : \Phi^0_{\nu_\tau}) \to (\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau})$$



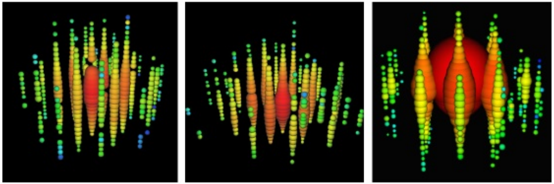
source: ν typical originated by high energetic proton collisions

$$p + p \to \pi^\pm \to \mu^\pm + \overset{(-)}{\nu}_\mu \to e^\pm + \overset{(-)}{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

Astrophysical flavor ratios at IceCube

IceCube (Feb '15) reported the detection of 36 neutrinos:

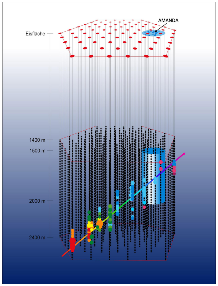
at 30 TeV to 2 PeV with extragalactic origin



Ernie: 1.0 Pev   Bert: 1.1 Pev   Big Bird: 2.0 Pev

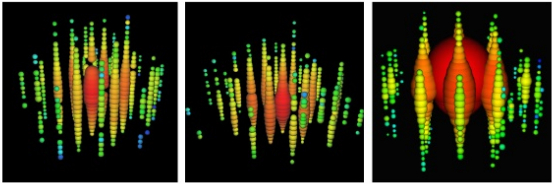
[M. G. Aartsen (IceCube Collaboration), Phys.Rev.Lett. 114 (2015) 17, 171102]

Astrophysical flavor ratios at IceCube



IceCube (Feb ’15) reported the detection of 36 neutrinos:

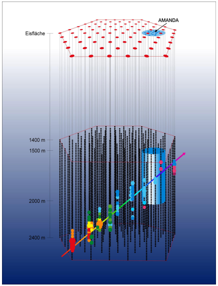
at 30 TeV to 2 PeV with extragalactic origin



Ernie: 1.0 Pev Bert: 1.1 Pev Big Bird: 2.0 Pev

[M. G. Aartsen (IceCube Collaboration), Phys.Rev.Lett. 114 (2015) 17, 171102]

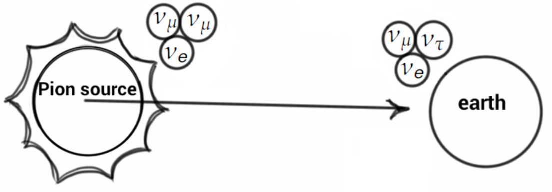
Astrophysical flavor ratios at IceCube



IceCube (Feb '15) reported the detection of 36 neutrinos:

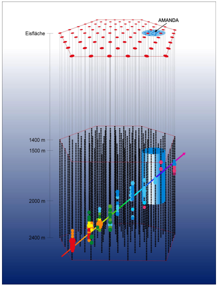
at 30 TeV to 2 PeV with extragalactic origin

$$(\Phi^0_{\nu_e} : \Phi^0_{\nu_\mu} : \Phi^0_{\nu_\tau}) \rightarrow (\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau})$$



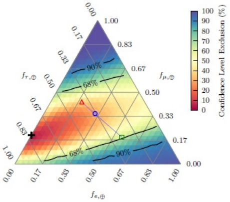
vacuum oscillation: (1:1:1)
is consistent with data, **but**

Astrophysical flavor ratios at IceCube

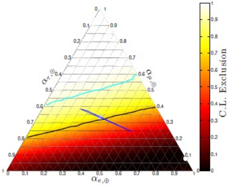


IceCube (Feb ’15) reported the detection of 36 neutrinos:

at 30 TeV to 2 PeV with extragalactic origin



[IceCube, 2015]
35 TeV - 1.9 PeV, Best Fit: (0:0.2:0.8)

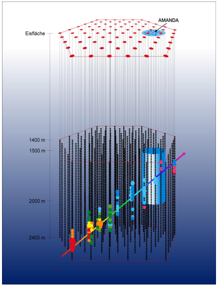


[Palomares-Ruiz, Vincent, Mena, 2015]
28 TeV - 3 PeV, Best Fit: (0.92:0.08:0)

vacuum oscillation: (1:1:1)
is consistent with data, **but**

best fit analysis: (1:0:0) & (0:0:1)
$\rightarrow$ **new physics**

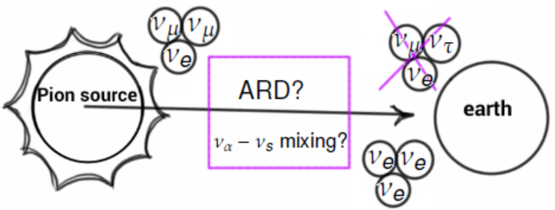
Astrophysical flavor ratios at IceCube



IceCube (Feb '15) reported the detection of 36 neutrinos:

at 30 TeV to 2 PeV with extragalactic origin

$$(\Phi^0_{\nu_e} : \Phi^0_{\nu_\mu} : \Phi^0_{\nu_\tau}) \rightarrow (\tilde{\Phi}_{\nu_e} : \tilde{\Phi}_{\nu_\mu} : \tilde{\Phi}_{\nu_\tau} : \Phi_{\nu_s}?)$$

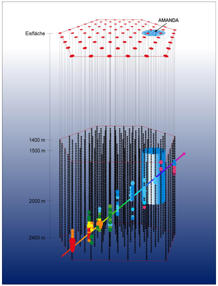


vacuum oscillation: (1:1:1) is consistent with data, **but**

best fit analysis: (1:0:0) & (0:0:1) $\rightarrow$ **new physics**

[Mena, Palomares-Ruiz, Vincent (Feb. '15), IceCube (Feb. '15)]

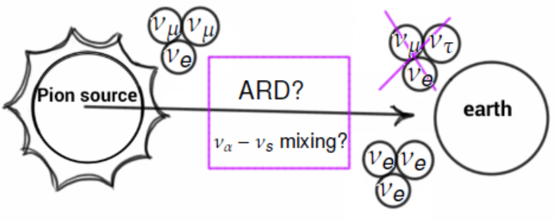
Astrophysical flavor ratios at IceCube



IceCube (Feb ’15) reported the detection of 36 neutrinos:

at 30 TeV to 2 PeV with extragalactic origin

$$(\Phi^0_{\nu_e} : \Phi^0_{\nu_\mu} : \Phi^0_{\nu_\tau}) \to (\tilde{\Phi}_{\nu_e} : \tilde{\Phi}_{\nu_\mu} : \tilde{\Phi}_{\nu_\tau} : \Phi_{\nu_s}?)$$



vacuum oscillation: (1:1:1) is consistent with data, **but**

best fit analysis: (1:0:0) & (0:0:1) $\to$ **new physics**

[Mena, Palomares-Ruiz, Vincent (Feb. ’15), IceCube (Feb. ’15)]

ν_s in astrophysical flavor ratios at IceCube?

$(1:2:0) \rightarrow (1:0:0)$
source earth

solution:
include ν_s mixing with ADR (extradim.),
so that $\nu_\mu, \nu_\tau \rightarrow \nu_s$

Neutrinofluxes[1]

$\Phi_\alpha = \sum_\beta P_{\alpha\beta} \Phi^0_\beta \quad , \quad \alpha, \beta \in \{l, s\}$

Oscillation probabilities

$P_{\nu_\beta \rightarrow \nu_\alpha} = P_{\beta\alpha} \approx \sum_j |U_{\beta j}|^2 |U_{\alpha j}|^2$

[1] [Pakvasa, Rodejohann, Weiler, JHEP 0802 (2008) 005]

ν_s in astrophysical flavor ratios at IceCube?

$(1:2:0) \rightarrow (1:0:0)$
source earth

solution:
include ν_s mixing with ADR (extradim.),
so that $\nu_\mu, \nu_\tau \rightarrow \nu_s$, with $s\theta_{\mu s} = s\theta_{\tau s}$

Neutrinofluxes[1]

$$\tilde{\Phi}_\alpha = \sum_\beta \tilde{P}_{\alpha\beta}\Phi^0_\beta \, , \quad \alpha, \beta \in \{l, s\}$$

Oscillation probabilities

$$\tilde{P}_{\beta\alpha} \approx \sum_j |\tilde{U}_{\beta j}(\theta_{\mu s}, \theta_{\tau s})|^2 |\tilde{U}_{\alpha j}(\theta_{\mu s}, \theta_{\tau s})|^2$$

$$\tilde{U} = \frac{1}{\sqrt{6}} \begin{pmatrix} 2 & \sqrt{2}c_\mu & -s_\tau \sqrt{2}s_\mu & c_\tau \sqrt{2}s_\mu \\ -1 & \sqrt{2}c_\mu & -s_\tau \sqrt{2}s_\mu + \sqrt{3}c_\tau & c_\tau \sqrt{2}s_\mu + \sqrt{3}s_\tau \\ -1 & \sqrt{2}c_\mu & -s_\tau \sqrt{2}s_\mu - \sqrt{3}c_\tau & c_\tau \sqrt{2}s_\mu - \sqrt{3}s_\tau \\ -0 & -\sqrt{6}s_\mu & -\sqrt{6}c_\mu s_\tau & \sqrt{6}c_\mu c_\tau \end{pmatrix}$$

$c_\alpha, c\theta_\alpha \,\hat{=}\, \cos\theta_\alpha$
$s_\alpha, s\theta_\alpha \,\hat{=}\, \sin\theta_\alpha$

[1] [Pakvasa, Rodejohann, Weiler, JHEP 0802 (2008) 005]

ν_s in astrophysical flavor ratios at IceCube?

$(1:2:0) \rightarrow (1:0:0)$
source earth

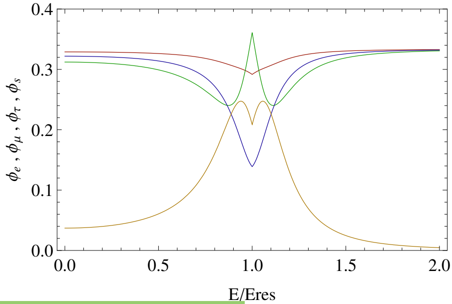
solution:
include ν_s mixing with ADR (extradim.),
so that $\nu_\mu, \nu_\tau \rightarrow \nu_s$, with $s\theta_{\mu s} = s\theta_{\tau s}$

Neutrinofluxes[1]

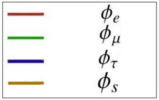
$\tilde{\Phi}_\alpha = \sum_\beta \tilde{P}_{\alpha\beta} \Phi^0_\beta \, , \quad \alpha, \beta \in \{l, s\}$

Oscillation probabilities

$\tilde{P}_{\beta\alpha} \approx \sum_j |\tilde{U}_{\beta j}(\theta_{\mu s}, \theta_{\tau s})|^2 |\tilde{U}_{\alpha j}(\theta_{\mu s}, \theta_{\tau s})|^2$



for $\sin^2\theta = 0.03$, $\Delta m^2 = 1\,\text{eV}^2$
best fit values from PDG



[EA, H. Päs, P. Sicking, arXiv: hep-ph\1410.0408]

ν_s in astrophysical flavor ratios at IceCube?

$(1:2:0) \to (1:0:0)$
source earth

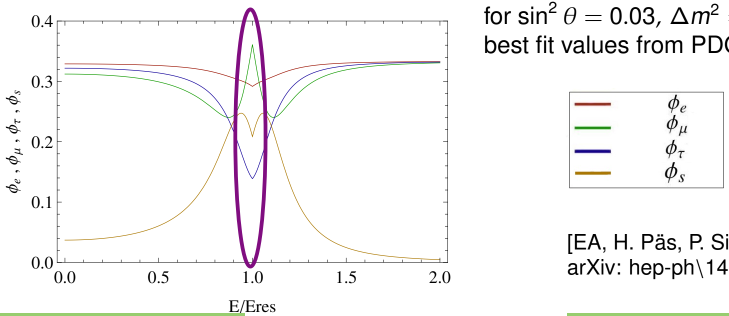
solution:
include ν_s mixing with ADR (extradim.),
so that $\nu_\mu, \nu_\tau \to \nu_s$, with $s\theta_{\mu s} = s\theta_{\tau s}$

Neutrinofluxes[1]

$$\tilde{\Phi}_\alpha = \sum_\beta \tilde{P}_{\alpha\beta} \Phi^0_\beta \,, \quad \alpha, \beta \in \{l, s\}$$

Oscillation probabilities

$$\tilde{P}_{\beta\alpha} \approx \sum_j |\tilde{U}_{\beta j}(\theta_{\mu s}, \theta_{\tau s})|^2 |\tilde{U}_{\alpha j}(\theta_{\mu s}, \theta_{\tau s})|^2$$



for $\sin^2\theta = 0.03$, $\Delta m^2 = 1\,\text{eV}^2$
best fit values from PDG

[EA, H. Päs, P. Sicking, arXiv: hep-ph\1410.0408]

ν_s in astrophysical flavor ratios at IceCube?

source	Φ_β^0	mixing	$\Phi_\beta(\theta^{\alpha s})$
Pion	1:2:0:0	none ($\theta^{\alpha s} = 0$)	1:1:1:0
		$\nu_e - \nu_s$	4:11:11:6
		$\nu_\mu - \nu_s$	5:5:5:3
		$(\nu_e, \nu_\mu) - \nu_s$	32:41:41:30
		$(\nu_\mu, \nu_\tau) - \nu_s$	21:26:10:15
Damped Muon	0:1:0:0	none ($\theta^{\alpha s} = 0$)	4:7:7:0
		$\nu_e - \nu_s$	4:9:9:2
		$\nu_\mu - \nu_s$	1: 2:2:1
		$(\nu_e, \nu_\mu) - \nu_s$	16:115:115:42
		$(\nu_\mu, \nu_\tau) - \nu_s$	7:16:4:9
Neutron Beam	1:0:0:0	none ($\theta^{\alpha s} = 0$)	5:2:2:0
		$\nu_e - \nu_s$	2:1:1:2
		$\nu_\mu - \nu_s$	3:1:1:1
		$(\nu_e, \nu_\mu) - \nu_s$	10:1:1:6
		$(\nu_\mu, \nu_\tau) - \nu_s$	35:14:14:9

mixing at resonance $E = E_{res}$

ν_s in astrophysical flavor ratios at IceCube?

source	Φ^0_β	mixing	$\Phi_\beta(\theta^{\alpha s})$
Pion	1:2:0:0	none ($\theta^{\alpha s} = 0$)	1:1:1:0
		$\nu_e - \nu_s$	4:11:11:6
		$\nu_\mu - \nu_s$	5:5:5:3
		$(\nu_e, \nu_\mu) - \nu_s$	32:41:41:30
		$(\nu_\mu, \nu_\tau) - \nu_s$	21:26:10:15
Damped Muon	0:1:0:0	none ($\theta^{\alpha s} = 0$)	4:7:7:0
		$\nu_e - \nu_s$	4:9:9:2
		$\nu_\mu - \nu_s$	1: 2:2:1
		$(\nu_e, \nu_\mu) - \nu_s$	16:115:115:42
		$(\nu_\mu, \nu_\tau) - \nu_s$	7:16:4:9
Neutron Beam	1:0:0:0	none ($\theta^{\alpha s} = 0$)	5:2:2:0
		$\nu_e - \nu_s$	2:1:1:2
		$\nu_\mu - \nu_s$	3:1:1:1
		$(\nu_e, \nu_\mu) - \nu_s$	10:1:1:6
		$(\nu_\mu, \nu_\tau) - \nu_s$	35:14:14:9

additionally examine:

- different sources
- different mixing

mixing at resonance $E = E_{res}$

ν_s in astrophysical flavor ratios at IceCube?

source	Φ^0_β	mixing	$\Phi_\beta(\theta^{\alpha s})$
Pion	1:2:0:0	none ($\theta^{\alpha s} = 0$)	1:1:1:0
		$\nu_e - \nu_s$	4:11:11:6
		$\nu_\mu - \nu_s$	5:5:5:3
		$(\nu_e, \nu_\mu) - \nu_s$	32:41:41:30
		$(\nu_\mu, \nu_\tau) - \nu_s$	21:26:10:15
Damped Muon	0:1:0:0	none ($\theta^{\alpha s} = 0$)	4:7:7:0
		$\nu_e - \nu_s$	4:9:9:2
		$\nu_\mu - \nu_s$	1: 2:2:1
		$(\nu_e, \nu_\mu) - \nu_s$	16:115:115:42
		$(\nu_\mu, \nu_\tau) - \nu_s$	7:16:4:9
Neutron Beam	1:0:0:0	none ($\theta^{\alpha s} = 0$)	5:2:2:0
		$\nu_e - \nu_s$	2:1:1:2
		$\nu_\mu - \nu_s$	3:1:1:1
		$(\nu_e, \nu_\mu) - \nu_s$	10:1:1:6
		$(\nu_\mu, \nu_\tau) - \nu_s$	35:14:14:9

additionally examine:

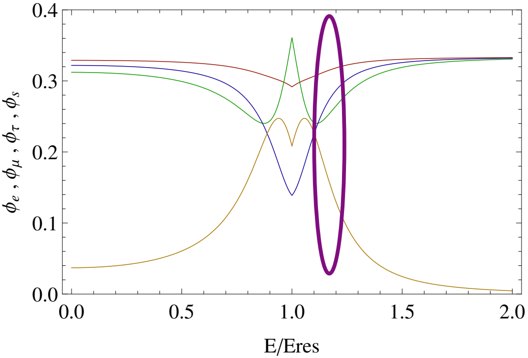
- different sources
- different mixing

↪ even at other energies it doesn't look too good

mixing at resonance $E = E_{res}$

ν_s in astrophysical flavor ratios at IceCube?

source	Φ^0_β	mixing	$\Phi_\beta(\theta^{\alpha s})$
Pion	1:2:0:0	none ($\theta^{\alpha s} = 0$)	1:1:1:0
Damp Muon			
Neutr Beam			
		$(\nu_\mu, \nu_\tau) - \nu_s$	35:14:14:9



additionally examine:

- different sources
- different mixing

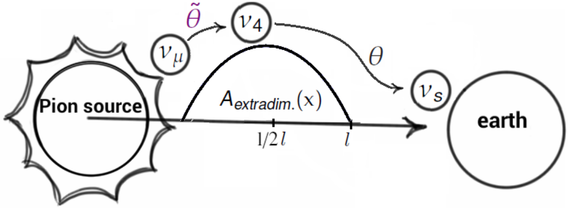
→ even at other energies it doesn't look too good

mixing at resonance $E = E_{res}$

ν_s in astrophysical flavor ratios at IceCube?

possible solution is an **adiabatic conversion** (MSW-like effect):

- nearly full conversion $\nu_\mu(\nu_\tau) \to \nu_s$ possible
- extradim. potential is slowly changing: $A_{ext}(x) = \epsilon(x)E$
- runs through resonance, ends in vacuum oscillation with same mass-eigenstate $|\nu_i\rangle$



oscillation propability

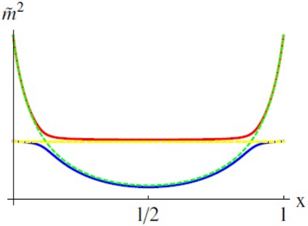
$$P_{\nu_e \to \nu_e} = \underbrace{1 - \frac{1}{2}\sin^2(2\tilde{\theta})}_{\frac{1}{2}-\frac{1}{2}\cos^2(2\tilde{\theta})} \quad \to \quad \tfrac{1}{2} - \tfrac{1}{2}\cos(2\theta)\cos(2\tilde{\theta})$$

[EA, H. Päs, P. Sicking, JCAP 1510 (2015) 10, 005]

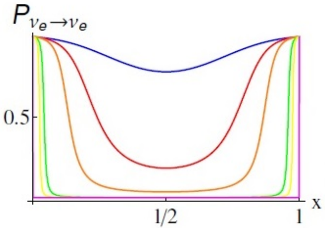
ν_s in astrophysical flavor ratios at IceCube?

- extradim. potential is slowly changing ($\tau_{system} \ll \tau_{interaction}$)
- $A_{ext}(x) = \epsilon(x)E = \left(1 - \frac{1}{\sqrt{1+k^2\,x(l-x)}}\right)E$
  two free parameter: warp factor k, periodic length l
- changing mass eigenstates:

$$\tilde{m}^2_{1/2} = -\frac{A}{2} \pm \frac{\Delta m^2}{2}\sqrt{\left(\frac{A(x)2E}{\Delta m^2} - cos(2\theta)\right)^2 + sin(2\theta)^2}$$



stays in massES, no level crossing

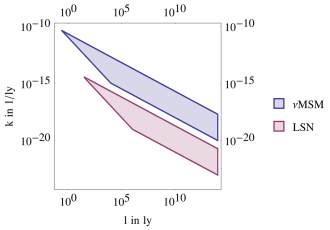


increasing E from blue to purble

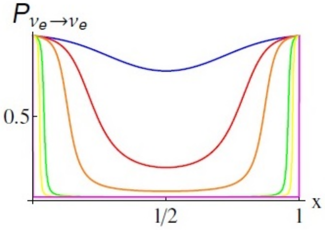
[EA, H. Päs, P. Sicking, JCAP 1510 (2015) 10, 005]

ν_s in astrophysical flavor ratios at IceCube?

- extradim. potential is slowly changing ($\tau_{system} \ll \tau_{interaction}$)
  two free parameter: warp factor k, periodic length l
- average over $\bar{P}$ (travel distance $\gg l$)



limits on l and k



increasing E from blue to purble

nearly full conversion is possible (1:2:0) → (4:1:1)

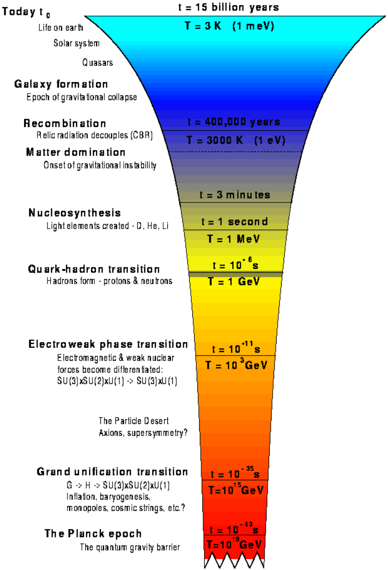
[EA, H. Päs, P. Sicking, JCAP 1510 (2015) 10, 005]

Big Bang Nucleosynthesis

Testing method for new physics, eg. introducing new particles

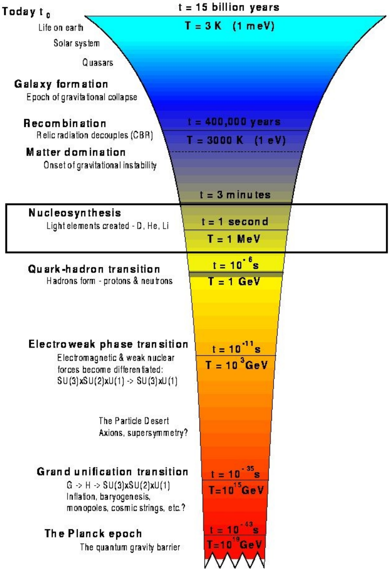
Big Bang Nucleosynthesis

Epochs in the early universe



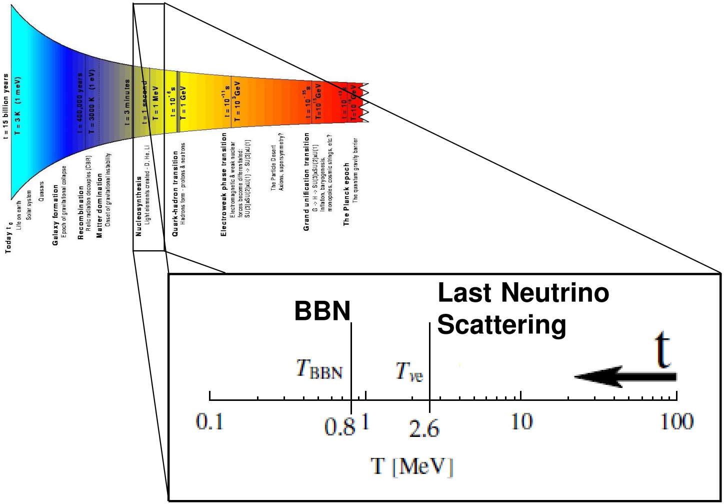
Big Bang Nucleosynthesis

Epochs in the early universe



Big Bang Nucleosynthesis

Time and temperature of the **epochs** in the early universe



Big Bang Nucleosynthesis

Time and temperature of the epochs in the early universe

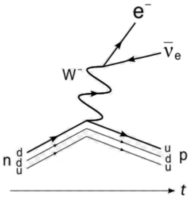
interactions **freeze out** when: $\Gamma(T_{epoch}) \lesssim H(T_{epoch})$

- **BBN (T_{BBN})**

  n,p freeze out and glue to nucleons: ^{4}He, De, Li...

  weak interaction

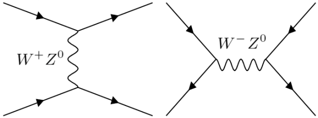
$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu_e} \\ \nu_e + n &\leftrightarrow p + e^- \\ e^+ + n &\leftrightarrow p + \bar{\nu_e} \end{aligned}$$



- **Last Neutrino-Scattering (T_{ν_e})**

  lepton-neutrino interaction

$$\begin{aligned} e^- + e^+ &\leftrightarrow \nu_l + \bar{\nu}_l \\ \nu_l + e^- &\leftrightarrow \nu_l + e^- \end{aligned}$$



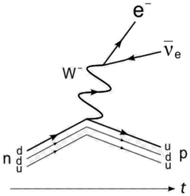
Big Bang Nucleosynthesis

BBN: temperature (T_{BBN}) in the early universe when the week interactions Γ_{BBN} freeze out

n,p freeze out and glue to nucleons:

^{4}He, De, Li...

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu}_e \\ \nu_e + n &\leftrightarrow p + e^- \\ e^+ + n &\leftrightarrow p + \bar{\nu}_e \end{aligned}$$

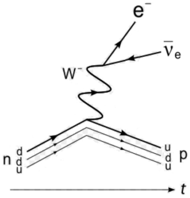


Big Bang Nucleosynthesis

BBN: temperature (T_{BBN}) in the early universe when the week interactions Γ_{BBN} freeze out

n,p freeze out and glue to nucleons:
^{4}He, De, Li...

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu_e} \\ \nu_e + n &\leftrightarrow p + e^- \\ e^+ + n &\leftrightarrow p + \bar{\nu_e} \end{aligned}$$



- $T_{BBN}^{theo.}$ reactions **freeze out**

$$\Gamma_{BBN}(T_{BBN}) \lesssim H(g_{eff}, T_{BBN})$$

- $T_{BBN}^{exp.}$ precisely measured, since ^{4}He abundance $Y(^4\mathrm{He})$ set limits

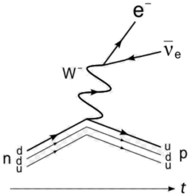
$$n_n/n_p \simeq e^{-\Delta M/T+(\mu_e-\mu_\nu)/T} \quad \propto \quad Y(^4\mathrm{He}) = 0.249 \pm 0.009 \quad \text{(measured)}$$

Big Bang Nucleosynthesis

BBN: temperature (T_{BBN}) in the early universe when the week interactions Γ_{BBN} freeze out

n,p freeze out and glue to nucleons: ^{4}He, De, Li...

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu_e} \\ \nu_e + n &\leftrightarrow p + e^- \\ e^+ + n &\leftrightarrow p + \bar{\nu_e} \end{aligned}$$



$T^{theo.}_{BBN}$ reactions **freeze out**

$$\Gamma_{BBN}(T_{BBN}) \lesssim H(g_{eff}, T_{BBN})$$

theory

$T^{exp.}_{BBN}$ precisely measured, since ^{4}He abundance $Y(^4\text{He})$ set limits

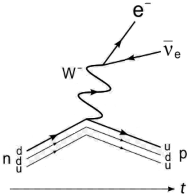
$$n_n/n_p \simeq e^{-\Delta M/T + (\mu_e - \mu_\nu)/T} \propto Y(^4\text{He}) = 0.249 \pm 0.009 \quad \text{(measured)}$$

Big Bang Nucleosynthesis

BBN: temperature (T_{BBN}) in the early universe when the week interactions Γ_{BBN} freeze out

n,p freeze out and glue to nucleons: ^{4}He, De, Li...

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu}_e \\ \nu_e + n &\leftrightarrow p + e^- \\ e^+ + n &\leftrightarrow p + \bar{\nu}_e \end{aligned}$$



$T_{BBN}^{theo.}$ reactions **freeze out**

$$\Gamma_{BBN}(T_{BBN}) \lesssim H(g_{eff}, T_{BBN})$$

theory

$T_{BBN}^{exp.}$ precisely measured, since ^{4}He abundance $Y(^4\text{He})$ set limits

$$n_n/n_p \simeq e^{-\Delta M/T + (\mu_e - \mu_\nu)/T} \propto Y(^4\text{He}) = 0.249 \pm 0.009 \quad \text{(measured)}$$

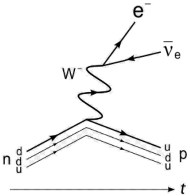
experiment

Big Bang Nucleosynthesis

BBN: temperature (T_{BBN}) in the early universe when the week interactions Γ_{BBN} freeze out

n,p freeze out and glue to nucleons: ^{4}He, De, Li...

$$\begin{array}{rcl} n & \leftrightarrow & p + e^- + \bar{\nu}_e \\ \nu_e + n & \leftrightarrow & p + e^- \\ e^+ + n & \leftrightarrow & p + \bar{\nu}_e \end{array}$$



$T_{BBN}^{theo.}$ reactions **freeze out**

$$\Gamma_{BBN}(T_{BBN}) = 2\langle n_e \cdot \sigma(E_e, p_e) \cdot |v_e|\rangle \quad \lesssim \quad H(g_{eff}, T_{BBN})$$

theory

✓ **in good agreement!**

$T_{BBN}^{exp.}$ precisely measured, since ^{4}He abundance $Y(^4\text{He})$ set limits

$$n_n/n_p \simeq e^{-\Delta M/T + (\mu_e - \mu_\nu)/T} \quad \propto \quad Y(^4\text{He}) = 0.249 \pm 0.009 \quad \text{(measured)}$$

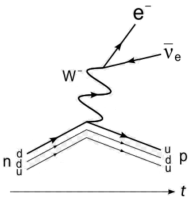
experiment

Big Bang Nucleosynthesis

BBN: temperature (T_{BBN}) in the early universe when the week interactions Γ_{BBN} freeze out

n,p freeze out and glue to nucleons:
^{4}He, De, Li...

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu_e} \\ \nu_e + n &\leftrightarrow p + e^- \\ e^+ + n &\leftrightarrow p + \bar{\nu_e} \end{aligned}$$



$T_{BBN}^{theo.}$ reactions **freeze out**

$$\Gamma_{BBN}(T_{BBN}) = 2\langle n_e \cdot \sigma(E_e, p_e) \cdot |v_e|\rangle \quad \lesssim \quad H(g_{eff}, T_{BBN})$$

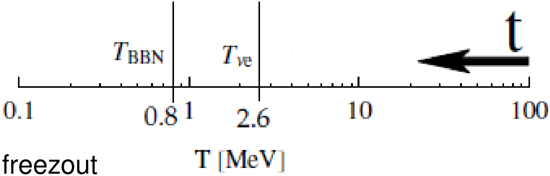
with $\nu_s - \nu_l$ **mixing** → T_{BBN} changed ↯ **no agreement now!**

$T_{BBN}^{exp.}$ precisely measured, since ^{4}He abundance $Y(^4\text{He})$ set limits

$$n_n/n_p \simeq e^{-\Delta M/T + (\mu_e - \mu_\nu)/T} \quad \propto \quad Y(^4\text{He}) = 0.249 \pm 0.009 \quad \text{(measured)}$$

Big Bang Nucleosynthesis

Solution: ν_s-production should be **frozen out** in the time before T_{BBN}



Timeline of freezout

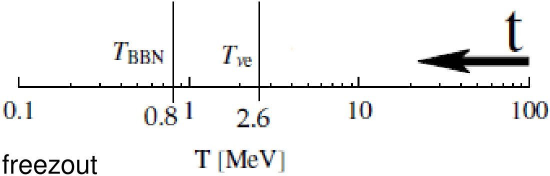
Big Bang Nucleosynthesis

Solution: ν_s-production should be **frozen out** in the time before T_{BBN}

- ν_s (singlets under the SM) are only present through oscillations with active neutrinos. ν_s-production: $\Gamma_{\nu_s} = \langle P_{\nu_\alpha \to \nu_s} \rangle \Gamma_{\nu_\alpha}$
- The freezing of the active neutrino interactions freeze the $\nu_s - \nu_\alpha$ oscillations at T_{ν_α}

freezing condition of ν_s-production

$$\Gamma_{\nu_s}(T_{\nu_\alpha}) \lesssim H \quad (T_{\nu_\alpha})$$



Timeline of freezout

Big Bang Nucleosynthesis

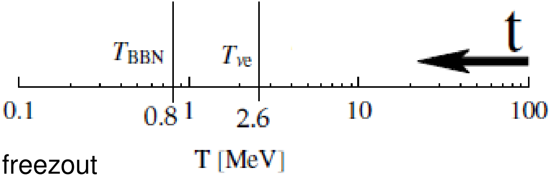
Solution: ν_s-production should be **frozen out** in the time before T_{BBN}

- ν_s (singlets under the SM) are only present through oscillations with active neutrinos. ν_s-production: $\Gamma_{\nu_s} = \langle P_{\nu_\alpha \to \nu_s} \rangle \Gamma_{\nu_\alpha}$
- The freezing of the active neutrino interactions freeze the $\nu_s - \nu_\alpha$ oscillations at T_{ν_α}

freezing condition of ν_s-production

$$\Gamma_{\nu_s}(T_{\nu_\alpha}) \lesssim H \quad (T_{\nu_\alpha})$$

$$\Gamma_{\nu_s} = \langle P_{\nu_\alpha \to \nu_s} \rangle \Gamma_{\nu_\alpha} \lesssim H$$



Timeline of freezout

Big Bang Nucleosynthesis

freezing condition of ν_s-production

$$\Gamma_{\nu_s} = \underbrace{\langle P_{\nu_\alpha \to \nu_s} \rangle}_{\text{has to be suppressed}} \Gamma_{\nu_\alpha} \lesssim H$$

$$\langle P_{\nu_l \to \nu_s}(\sin(2\theta), \Delta m^2) \rangle = \frac{1}{2} \sin^2(2\tilde{\theta}) = \frac{1}{2} \frac{\sin^2(2\theta)}{\cos^2(2\theta)\left(\frac{2E\,A(E)}{\Delta m^2 \cos(2\theta)}\right)^2 + \sin^2(2\theta)} \to 0$$

either potential of ADR is high enough

or oscillation parameters are suppressed: $\sin(2\theta), \Delta m^2 \to 0$

Big Bang Nucleosynthesis

freezing condition of ν_s-production

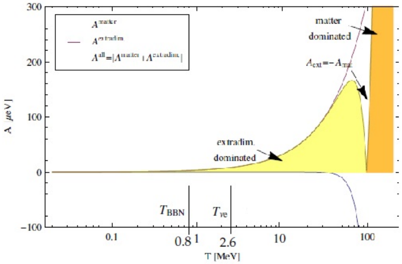
$$\Gamma_{\nu_s} = \underbrace{\langle P_{\nu_\alpha \to \nu_s} \rangle}_{\text{has to be suppressed}} \Gamma_{\nu_\alpha} \lesssim H$$

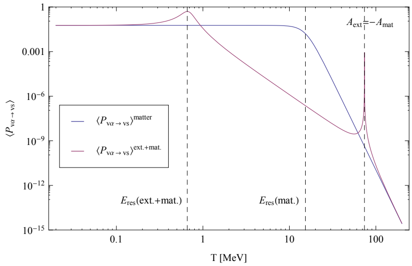
$$\langle P_{\nu_l \to \nu_s}(\sin(2\theta), \Delta m^2) \rangle = \frac{1}{2} \sin^2(2\tilde{\theta}) = \frac{1}{2} \frac{\sin^2(2\theta)}{\cos^2(2\theta)\left(\frac{2E\,A(E)}{\Delta m^2 \cos(2\theta)}\right)^2 + \sin^2(2\theta)} \to 0$$

either potential of ADR is high enough

or oscillation parameters are suppressed: $\sin(2\theta), \Delta m^2 \to 0$

Big Bang Nucleosynthesis





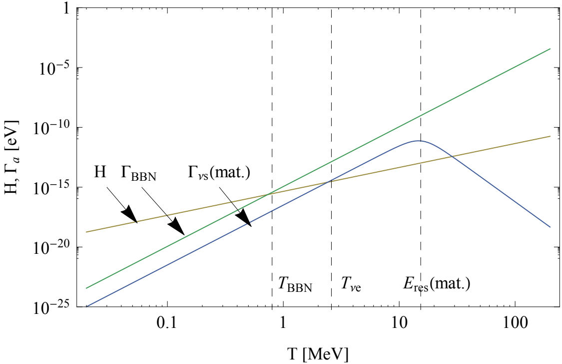
<u>Time evolution of the:</u>

- hot dense **matter potential**: $A_{mat.} \propto T^5$
- extradimensional potential: $A_{ext.} \propto T$
- both: $A_{all} = A_{ext.} + A_{mat.} \propto T + T^5$

oscillation probability $\langle P_{\nu_\alpha \to \nu_s}(A) \rangle$

(used param. $\sin(2\theta) = 0.03$, $\Delta m^2 = 1\,\text{eV}^2$)

Big Bang Nucleosynthesis



$\cancel{\tilde{\Gamma}_{\nu_s} < H}$

ν_s–oscillations are present

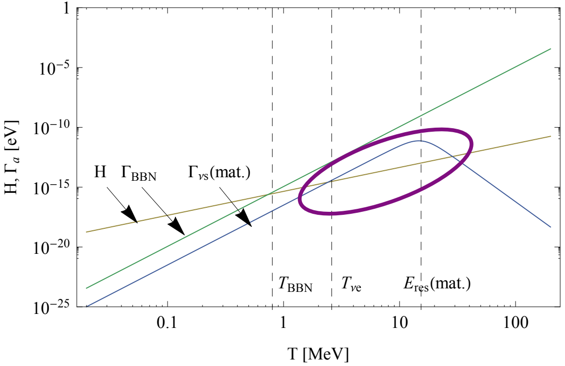
To suppress ν_s–oscillations: $\sin(2\theta), \Delta m^2 \to 0$

ADR by a hot dense **matter potential** in the early universe: $A_{mat.} \propto T^5$

$\tilde{\Gamma}_{\nu_s} = \langle P(A_{mat.}) \rangle \Gamma_{\nu_\alpha}$

(used param. $\sin(2\theta) = 0.03$, $\Delta m^2 = 1\ \mathrm{eV}^2$)

Big Bang Nucleosynthesis



$\cancel{\tilde{\Gamma}_{\nu_s} < H}$

ν_s–oscillations are present

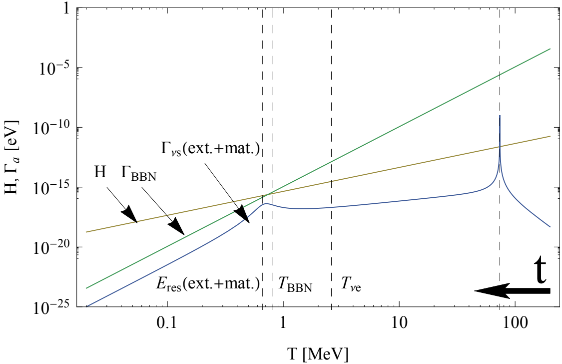
To suppress ν_s–oscillations: $\sin(2\theta), \Delta m^2 \to 0$

ADR by a hot dense **matter potential** in the early universe: $A_{mat.} \propto T^5$

$\tilde{\Gamma}_{\nu_s} = \langle P(A_{mat.})\rangle \Gamma_{\nu_\alpha}$

(used param. $\sin(2\theta) = 0.03$, $\Delta m^2 = 1$ eV^2)

Big Bang Nucleosynthesis



$\tilde{\Gamma}_{\nu_s} < H$

ADR caused by extra dimensions suppress ν_s–oscillation in the early universe:

$\sin(2\theta), \Delta m^2 \not\to 0$

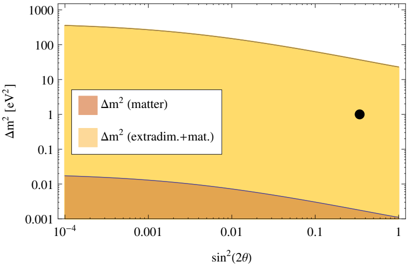
new additional effective potential from **extradim.**: $A_{all} = A_{ext.} + A_{mat.}$

$$\tilde{\Gamma}_{\nu_s} = \langle P(A_{all}) \rangle \Gamma_{\nu_\alpha}$$

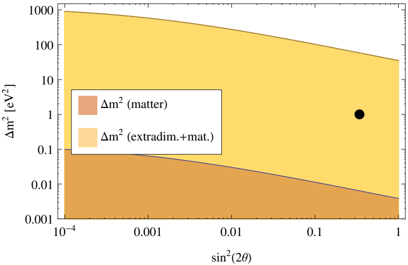
(used param. $\sin(2\theta) = 0.03$, $\Delta m^2 = 1$ eV^2)

Big Bang Nucleosynthesis

Reference point is at $\sin^2(\theta_0) = 0.03$, $\Delta m^2 = 1\,\mathrm{eV}^2$, [Kopp et al. JHEP 1305, 050]



$\nu_e - \nu_s$ oscillation



$\nu_{\mu,\tau} - \nu_s$ oscillation

- without extradim. suppressed oscillation parameter $\Delta m^2, sin^2(2\theta) \rightarrow\ 0$
- larger parameter space allowed with ADR caused by extradim.

[EA, H. Päs, manuscript in preparation]

Summary

Neutrino oscillations with sterile neutrinos and background potentials (ADR) - like extra dimension:

- were constructed to solve neutrino Anomalies (and as an ADD model: weakness of gravity)
- can explain the best fit analysis of high energy IceCube neutrinos via $\nu_s - \nu_l$ mixing with adiabatic conversion (Φ_{ν_μ},$\Phi_{\nu_\tau} \rightarrow \Phi_{\nu_s}$)
- makes ν_s compatible with BBN, sets softer limits on $\nu_s - \nu_l$ neutrino mixing parameters

Summary

Neutrino oscillations with sterile neutrinos and background potentials (ADR) - like extra dimension:

- were constructed to solve neutrino Anomalies (and as an ADD model: weakness of gravity)
- can explain the best fit analysis of high energy IceCube neutrinos via $\nu_s - \nu_l$ mixing with adiabatic conversion ($\Phi_{\nu_\mu}, \Phi_{\nu_\tau} \rightarrow \Phi_{\nu_s}$)
- makes ν_s compatible with BBN, sets softer limits on $\nu_s - \nu_l$ neutrino mixing parameters

Thank you!