Challenges of Vacuum Structure in Cosmology

Johann RAFELSKI

Department of Physics, The University of Arizona

& Guest at LS Habs-Physik Department
LM Universität Münich

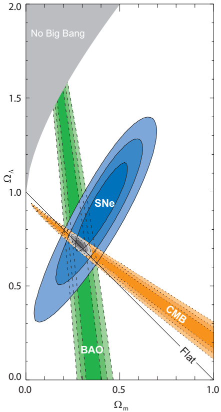
Supported by: The U.S. Department of Energy grant DE-FG02-04ER4131

and by DFG Cluster of Excellence MAP (Munich Centre of Advanced Photonics)

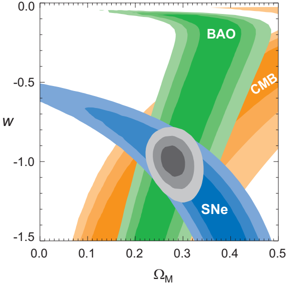
The great riddle 1: Accelerating Universe

$\rightarrow$ Dark Energy $\rightarrow$We live in FALSE vacuum

Observation: accelerating expansion of the universe. Many explanations proposed. Einstein: $\Lambda \equiv G_N \lambda$ fits ALL data.



Frieman et al, Annu.Rev. Astron. Astrophys. 46 (2008) 385



Data from supernovae (SNe), Cosmic Microwave Background (CMB), Baryon Acoustical Oscillations (BAO); includes global sky surveys, Sachs-Wolfe effect, results in:

$$\lambda = 0.73 \pm 0.03 \rho_c$$

where

$$\rho_c = \frac{3H_0^2}{8\pi G_N} = 10.54 h^2 \mathrm{GeV/m^3}$$

and with

$$h = 0.73 \pm 0.03$$

we find

$$\lambda \simeq 4.1 \pm 0.5 \mathrm{GeV/m^3}$$
$$\simeq (3.1 \pm 0.8\,\mathrm{meV})^4$$
$$\simeq 6.6 \pm 0.8\, 10^{-10}\,\mathrm{J/m^3}$$

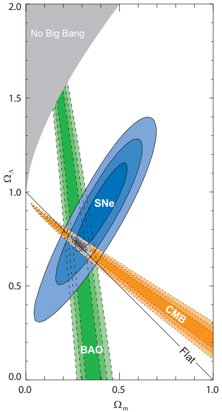
$$\omega \equiv P/\rho = -0.94 \pm 0.1$$

in true vacuum: $\lambda = 0$.

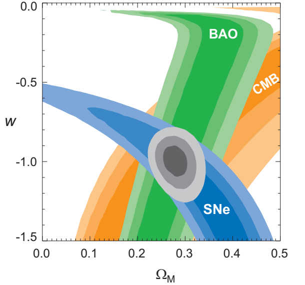
The great riddle 1: Accelerating Universe

→ Dark Energy →We live in FALSE vacuum

Observation: accelerating expansion of the universe. Many explanations proposed. Einstein: $\Lambda \equiv G_N \lambda$ fits ALL data.



Frieman et al, Annu.Rev. Astron. Astrophys. 46 (2008) 385



Data from supernovae (SNe), Cosmic Microwave Background (CMB), Baryon Acoustical Oscillations (BAO); includes global sky surveys, Sachs-Wolfe effect, results in:

$$\omega \equiv P/\rho = -0.94 \pm 0.1$$

$$\lambda = 0.73 \pm 0.03 \rho_c$$

where

$$\rho_c = \frac{3H_0^2}{8\pi G_N} = 10.54 h^2 \mathrm{GeV/m}^3$$

and with

$$h = 0.73 \pm 0.03$$

we find

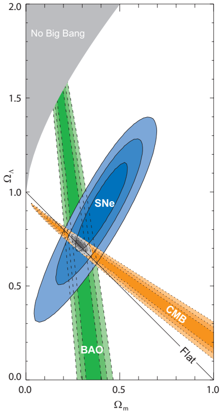
$$\lambda \simeq 4.1 \pm 0.5 \mathrm{GeV/m}^3$$
$$\simeq (3.1 \pm 0.8\,\mathrm{meV})^4$$
$$\simeq 6.6 \pm 0.8\, 10^{-10}\,\mathrm{J/m}^3$$

in true vacuum: $\lambda = 0$.

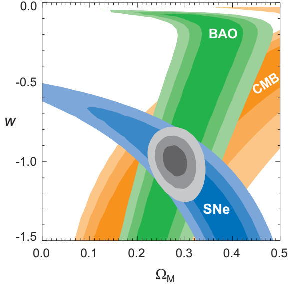
The great riddle 1: Accelerating Universe

$\rightarrow$ Dark Energy $\rightarrow$We live in FALSE vacuum

Observation: accelerating expansion of the universe. Many explanations proposed. Einstein: $\Lambda \equiv G_N \lambda$ fits ALL data.



Frieman et al, Annu.Rev. Astron. Astrophys. 46 (2008) 385



Data from supernovae (SNe), Cosmic Microwave Background (CMB), Baryon Acoustical Oscillations (BAO); includes global sky surveys, Sachs-Wolfe effect, results in:

$$\lambda = 0.73 \pm 0.03 \rho_c$$

where

$$\rho_c = \frac{3H_0^2}{8\pi G_N} = 10.54 h^2 \mathrm{GeV/m}^3$$

and with

$$h = 0.73 \pm 0.03$$

we find

$$\lambda \simeq 4.1 \pm 0.5 \mathrm{GeV/m}^3$$
$$\simeq (3.1 \pm 0.8\,\mathrm{meV})^4$$
$$\simeq 6.6 \pm 0.8\, 10^{-10}\ \mathrm{J/m}^3$$

$$\omega \equiv P/\rho = -0.94 \pm 0.1$$

in true vacuum: $\lambda = 0$.

The great riddle 2: Vacuum fluctuations do not gravitate

OR: False vacuum has the wrong energy scale. What do we expect? Consider vacuum energy obtained by summing zero-point energy:

$$\langle\epsilon\rangle_{\rm matter} = -2_s \cdot 2_p \cdot \int_0^{M_p} \frac{4\pi k^2 dk}{(2\pi)^3}\frac{1}{2}\sqrt{k^2+m^2} \simeq -\frac{M_p^4}{16\pi^2}$$

Summing over the known matter fields, $\langle\epsilon\rangle \simeq 10^{130}\lambda$

No known framework (including realistic supersymmetric theory) cancels near to *130 orders of magnitude*

No solution in sight within the realm of conventional QFT/Gravity. However, it is the general belief that a solution is forthcoming when gravity and quantum physics are made consistent.

The great riddle 2: Vacuum fluctuations do not gravitate

OR: False vacuum has the wrong energy scale. What do we expect? Consider vacuum energy obtained by summing zero-point energy:

$$\langle \epsilon \rangle_{\rm matter} = -2_s \cdot 2_p \cdot \int_0^{M_p} \frac{4\pi k^2 dk}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2} \simeq -\frac{M_p^4}{16\pi^2}$$

Summing over the known matter fields, $\langle \epsilon \rangle \simeq 10^{130} \lambda$

No known framework (including realistic supersymmetric theory) cancels near to *130 orders of magnitude*

No solution in sight within the realm of conventional QFT/Gravity. However, it is the general belief that a solution is forthcoming when gravity and quantum physics are made consistent.

The great riddle 2: Vacuum fluctuations do not gravitate

OR: False vacuum has the wrong energy scale. What do we expect? Consider vacuum energy obtained by summing zero-point energy:

$$\langle\epsilon\rangle_{\rm matter} = -2_s \cdot 2_p \cdot \int_0^{M_p} \frac{4\pi k^2 dk}{(2\pi)^3} \frac{1}{2}\sqrt{k^2+m^2} \simeq -\frac{M_p^4}{16\pi^2}$$

Summing over the known matter fields, $\langle\epsilon\rangle \simeq 10^{130}\lambda$

No known framework (including realistic supersymmetric theory) cancels near to *130 orders of magnitude*

No solution in sight within the realm of conventional QFT/Gravity. However, it is the general belief that a solution is forthcoming when gravity and quantum physics are made consistent.

The great riddle 3: True vacuum does not gravitate, yet

a)QCD Vacuum is non-trivial, has a 'permanent' structure:

vacuum state defined by $\langle F^a_{\mu\nu}\rangle_V = 0,\ \langle \vec{E}^a\rangle_V = 0,\ \langle \vec{B}^a\rangle_V = 0$

in true vacuum we have $\langle \frac{\alpha_s}{\pi} G^2 \rangle_V = [330(50)\,\mathrm{MeV}]^4$, vacuum dominated by

color – magnetic field fluctuations : $\langle B^2\rangle = \frac{1}{2}\langle G^2\rangle + \langle E^2\rangle$

this in turn drives quark condensate :$\langle \bar{u}u + \bar{d}d\rangle_V = -2[225(25)\,\mathrm{MeV}]^3$.

b) EW Vacuum is non-trivial, has a SSB structure:

$\langle H\rangle = 0.248$ TeV . $M_i = g_i\langle H\rangle/\sqrt{2}$ so $g_t = 0.99$, WHY?

can we not find meV dark energy vacuum deformation within GeV, TeV vacuum structure???

and, what about $\Delta m_\nu = 10 - 100$ meV , is it related to or not to λ?

The great riddle 3: True vacuum does not gravitate, yet

a)QCD Vacuum is non-trivial, has a ‘permanent’ structure:

vacuum state defined by $\langle F^a_{\mu\nu}\rangle_V = 0,\ \langle\vec{E}^a\rangle_V = 0,\ \langle\vec{B}^a\rangle_V = 0$

in true vacuum we have $\langle\frac{\alpha_s}{\pi}G^2\rangle_V = [330(50)\,\mathrm{MeV}]^4$, vacuum dominated by

color – magnetic field fluctuations : $\langle B^2\rangle = \frac{1}{2}\langle G^2\rangle + \langle E^2\rangle$

this in turn drives quark condensate :$\langle\bar{u}u + \bar{d}d\rangle_V = -2[225(25)\,\mathrm{MeV}]^3$.

b) EW Vacuum is non-trivial, has a SSB structure:

$\langle H\rangle = 0.248$ TeV . $M_i = g_i\langle H\rangle/\sqrt{2}$ so $g_t = 0.99$, WHY?

can we not find meV dark energy vacuum deformation within GeV, TeV vacuum structure???

and, what about $\Delta m_\nu = 10 - 100$ meV , is it related to or not to λ?

Release of dark energy

We should not expect explosive decay of the vacuum accompanied by a shock wave since the energy released is very small and probably not sufficient to maintain combustion – as evidenced by the fact that the Universe is still (mostly) in the false ground state.

The energy of the false vacuum quench should in some part turn to radiation-heat:

$$\lambda = \frac{E}{V} = \frac{\pi^2}{30} 2_S T_{\rm eq}^4 \qquad T_{\rm eq} = 0.9 \times 3.1 {\rm meV/k} = 32{\rm K}$$

The experimental device is traversing the Universe at a relatively high speed $v \simeq 300$ km/s wrt to CMB. Thus the naive argument is that the device experiences a heat flux:

$$J_Q = \lambda v = 2\,10^{-4} \frac{\rm J}{\rm s\,m^2}$$

Release of dark energy

We should not expect explosive decay of the vacuum accompanied by a shock wave since the energy released is very small and probably not sufficient to maintain combustion – as evidenced by the fact that the Universe is still (mostly) in the false ground state.

The energy of the false vacuum quench should in some part turn to radiation-heat:

$$\lambda = \frac{E}{V} = \frac{\pi^2}{30} 2_s T_{\rm eq}^4 \qquad T_{\rm eq} = 0.9 \times 3.1 {\rm meV}/{\rm k} = 32{\rm K}$$

The experimental device is traversing the Universe at a relatively high speed $v \simeq 300$ km/s wrt to CMB. Thus the naive argument is that the device experiences a heat flux:

$$J_Q = \lambda v = 2\,10^{-4} \frac{\rm J}{\rm s\,m^2}$$

Release of dark energy

We should not expect explosive decay of the vacuum accompanied by a shock wave since the energy released is very small and probably not sufficient to maintain combustion – as evidenced by the fact that the Universe is still (mostly) in the false ground state.

The energy of the false vacuum quench should in some part turn to radiation-heat:

$$\lambda = \frac{E}{V} = \frac{\pi^2}{30} 2_s T_{\rm eq}^4 \qquad T_{\rm eq} = 0.9 \times 3.1 \mathrm{meV/k} = 32\mathrm{K}$$

The experimental device is traversing the Universe at a relatively high speed $v \simeq 300$ km/s wrt to CMB. Thus the naive argument is that the device experiences a heat flux:

$$J_Q = \lambda v = 2\,10^{-4} \frac{\mathrm{J}}{\mathrm{s\,m^2}}$$

Absolute Motion?

However, as pointed out by B. Müller and T. Cohen, the vacuum state in a Lorentz symmetric theory cannot be a priori a select frame of reference, and thus we cannot detect the motion of any experimental apparatus with respect to the vacuum. The concept of a relative observer-vacuum velocity appears ill defined. There should be no heat flow resulting from vacuum combustion!

However, as pointed out by Einstein (see last transparency), since we make vacuum in part 'ponderable' when we can induce a local change of the vacuum, we break Lorentz symmetry. This is akin to the cosmologic Robertson-Walker Lorentz-variance but the vacuum state is a much more local phenomenon.

One of the key tasks must be the understanding of the rate of heat flow from the vacuum quench to a local frame of reference in which the quenching of the vacuum experiment operates. It seems to me that a thermally insulated vacuum conversion experimental system MUST appear to have a small but noticeable heat influx leak described in a good approximation by the heat flow formula.

As noted by Müller and Cohen this is an effect beyond the measurement of the relative velocity with a privileged frame of reference such as is CMB frame which is conform with Lorentz symmetry.

Absolute Motion?

However, as pointed out by B. Müller and T. Cohen, the vacuum state in a Lorentz symmetric theory cannot be a priori a select frame of reference, and thus we cannot detect the motion of any experimental apparatus with respect to the vacuum. The concept of a relative observer-vacuum velocity appears ill defined. There should be no heat flow resulting from vacuum combustion!

However, as pointed out by Einstein (see last transparency), since we make vacuum in part 'ponderable' when we can induce a local change of the vacuum, we break Lorentz symmetry. This is akin to the cosmologic Robertson-Walker Lorentz-variance but the vacuum state is a much more local phenomenon.

One of the key tasks must be the understanding of the rate of heat flow from the vacuum quench to a local frame of reference in which the quenching of the vacuum experiment operates. It seems to me that a thermally insulated vacuum conversion experimental system MUST appear to have a small but noticeable heat influx leak described in a good approximation by the heat flow formula.

As noted by Müller and Cohen this is an effect beyond the measurement of the relative velocity with a privileged frame of reference such as is CMB frame which is conform with Lorentz symmetry.

Absolute Motion?

However, as pointed out by B. Müller and T. Cohen, the vacuum state in a Lorentz symmetric theory cannot be a priori a select frame of reference, and thus we cannot detect the motion of any experimental apparatus with respect to the vacuum. The concept of a relative observer-vacuum velocity appears ill defined. There should be no heat flow resulting from vacuum combustion!

However, as pointed out by Einstein (see last transparency), since we make vacuum in part 'ponderable' when we can induce a local change of the vacuum, we break Lorentz symmetry. This is akin to the cosmologic Robertson-Walker Lorentz-variance but the vacuum state is a much more local phenomenon.

One of the key tasks must be the understanding of the rate of heat flow from the vacuum quench to a local frame of reference in which the quenching of the vacuum experiment operates. It seems to me that a thermally insulated vacuum conversion experimental system MUST appear to have a small but noticeable heat influx leak described in a good approximation by the heat flow formula.

As noted by Müller and Cohen this is an effect beyond the measurement of the relative velocity with a privileged frame of reference such as is CMB frame which is conform with Lorentz symmetry.

Absolute Motion?

However, as pointed out by B. Müller and T. Cohen, the vacuum state in a Lorentz symmetric theory cannot be a priori a select frame of reference, and thus we cannot detect the motion of any experimental apparatus with respect to the vacuum. The concept of a relative observer-vacuum velocity appears ill defined. There should be no heat flow resulting from vacuum combustion!

However, as pointed out by Einstein (see last transparency), since we make vacuum in part ‘ponderable’ when we can induce a local change of the vacuum, we break Lorentz symmetry. This is akin to the cosmologic Robertson-Walker Lorentz-variance but the vacuum state is a much more local phenomenon.

One of the key tasks must be the understanding of the rate of heat flow from the vacuum quench to a local frame of reference in which the quenching of the vacuum experiment operates. It seems to me that a thermally insulated vacuum conversion experimental system MUST appear to have a small but noticeable heat influx leak described in a good approximation by the heat flow formula.

As noted by Müller and Cohen this is an effect beyond the measurement of the relative velocity with a privileged frame of reference such as is CMB frame which is conform with Lorentz symmetry.

Vacuum quench by QCD Field, size scale fm

We hope that we can quench the false vacuum when we apply ‘external’ fields. Experiment would consist of catalyzing false vacuum decay to ground state.

We study volume traversed by atomic nuclei, and determine if it is converted into true vacuum due to the action of nuclear QCD and QED fields.

A large material object could quench the space volume it traverses. Experimental signature is that the object cannot get cold. Interestingly, minimum moon $T = 15$–40K is noted for deep craters near dark polar regions.

It would further seem that with reference to the cosmological frame the motion of a test body in the Universe is defined, despite Müller-Cohen argument and thus a long metal rod properly oriented in the Universe gets hotter on the one end facing the cosmic motion vector.

Note: on Earth the experiment is more difficult, since we are under 1000g/cm^2 of air which (in the event) reduces the flux of false vacuum. Perhaps a high mountain location could work. ALMA is at 5000m

Natural and man made object exposed to Sun light absorb solar heat and are permanently “warm". The dark side of the moon (28 day ‘moon-day’ means 14 days darkness) could be of interest, remote sensing may detect appropriate heat periodicity.

Vacuum quench by QCD Field, size scale fm

We hope that we can quench the false vacuum when we apply ‘external’ fields. Experiment would consist of catalyzing false vacuum decay to ground state.

We study volume traversed by atomic nuclei, and determine if it is converted into true vacuum due to the action of nuclear QCD and QED fields.

A large material object could quench the space volume it traverses. Experimental signature is that the object cannot get cold. Interestingly, minimum moon $T = 15$–40K is noted for deep craters near dark polar regions.

It would further seem that with reference to the cosmological frame the motion of a test body in the Universe is defined, despite Müller-Cohen argument and thus a long metal rod properly oriented in the Universe gets hotter on the one end facing the cosmic motion vector.

Note: on Earth the experiment is more difficult, since we are under 1000g/cm^2 of air which (in the event) reduces the flux of false vacuum. Perhaps a high mountain location could work. ALMA is at 5000m

Natural and man made object exposed to Sun light absorb solar heat and are permanently “warm". The dark side of the moon (28 day ‘moon-day’ means 14 days darkness) could be of interest, remote sensing may detect appropriate heat periodicity.

Vacuum quench by QCD Field, size scale fm

We hope that we can quench the false vacuum when we apply ‘external’ fields. Experiment would consist of catalyzing false vacuum decay to ground state.

We study volume traversed by atomic nuclei, and determine if it is converted into true vacuum due to the action of nuclear QCD and QED fields.

A large material object could quench the space volume it traverses. Experimental signature is that the object cannot get cold. Interestingly, minimum moon $T = 15$–40K is noted for deep craters near dark polar regions.

It would further seem that with reference to the cosmological frame the motion of a test body in the Universe is defined, despite Müller-Cohen argument and thus a long metal rod properly oriented in the Universe gets hotter on the one end facing the cosmic motion vector.

Note: on Earth the experiment is more difficult, since we are under 1000g/cm^2 of air which (in the event) reduces the flux of false vacuum. Perhaps a high mountain location could work. ALMA is at 5000m

Natural and man made object exposed to Sun light absorb solar heat and are permanently “warm". The dark side of the moon (28 day ‘moon-day’ means 14 days darkness) could be of interest, remote sensing may detect appropriate heat periodicity.

Vacuum quench by QCD Field, size scale fm

We hope that we can quench the false vacuum when we apply ‘external’ fields. Experiment would consist of catalyzing false vacuum decay to ground state.

We study volume traversed by atomic nuclei, and determine if it is converted into true vacuum due to the action of nuclear QCD and QED fields.

A large material object could quench the space volume it traverses. Experimental signature is that the object cannot get cold. Interestingly, minimum moon $T = 15$–40K is noted for deep craters near dark polar regions.

It would further seem that with reference to the cosmological frame the motion of a test body in the Universe is defined, despite Müller-Cohen argument and thus a long metal rod properly oriented in the Universe gets hotter on the one end facing the cosmic motion vector.

Note: on Earth the experiment is more difficult, since we are under 1000g/cm^2 of air which (in the event) reduces the flux of false vacuum. Perhaps a high mountain location could work. ALMA is at 5000m

Natural and man made object exposed to Sun light absorb solar heat and are permanently “warm". The dark side of the moon (28 day ‘moon-day’ means 14 days darkness) could be of interest, remote sensing may detect appropriate heat periodicity.

Vacuum quench by QCD Field, size scale fm

We hope that we can quench the false vacuum when we apply 'external' fields. Experiment would consist of catalyzing false vacuum decay to ground state.

We study volume traversed by atomic nuclei, and determine if it is converted into true vacuum due to the action of nuclear QCD and QED fields.

A large material object could quench the space volume it traverses. Experimental signature is that the object cannot get cold. Interestingly, minimum moon $T = 15$–40K is noted for deep craters near dark polar regions.

It would further seem that with reference to the cosmological frame the motion of a test body in the Universe is defined, despite Müller-Cohen argument and thus a long metal rod properly oriented in the Universe gets hotter on the one end facing the cosmic motion vector.

Note: on Earth the experiment is more difficult, since we are under 1000g/cm^2 of air which (in the event) reduces the flux of false vacuum. Perhaps a high mountain location could work. ALMA is at 5000m

Natural and man made object exposed to Sun light absorb solar heat and are permanently “warm". The dark side of the moon (28 day 'moon-day' means 14 days darkness) could be of interest, remote sensing may detect appropriate heat periodicity.

Vacuum quench by QCD Field, size scale fm

We hope that we can quench the false vacuum when we apply ‘external’ fields. Experiment would consist of catalyzing false vacuum decay to ground state.

We study volume traversed by atomic nuclei, and determine if it is converted into true vacuum due to the action of nuclear QCD and QED fields.

A large material object could quench the space volume it traverses. Experimental signature is that the object cannot get cold. Interestingly, minimum moon $T = 15$–40K is noted for deep craters near dark polar regions.

It would further seem that with reference to the cosmological frame the motion of a test body in the Universe is defined, despite Müller-Cohen argument and thus a long metal rod properly oriented in the Universe gets hotter on the one end facing the cosmic motion vector.

Note: on Earth the experiment is more difficult, since we are under 1000g/cm^2 of air which (in the event) reduces the flux of false vacuum. Perhaps a high mountain location could work. ALMA is at 5000m

Natural and man made object exposed to Sun light absorb solar heat and are permanently “warm". The dark side of the moon (28 day ‘moon-day’ means 14 days darkness) could be of interest, remote sensing may detect appropriate heat periodicity.

Vacuum quench by by QED Field, size scale micron

Recall: $\hbar c = 197\,\mathrm{MeV\,fm} = 197\,\mu\,\mathrm{meV}$

$$L = 2\pi\frac{\hbar c}{m_\nu} = 1\mu\mathrm{m} \quad \text{for } m_\nu = 1.24\,\text{eV}$$

Strong (laser) fields at micron scale can be man-made and could help quench the vacuum in particular if scale of dark energy $\lambda = 100\ \text{meV}^4$ and neutrino mass, $\Delta m_{12} = 8.9\text{meV}$ and $\Delta m_{13} = 49\text{meV}$ are related. Absolute neutrino mass scale not known but $m_{1,2,3} < 2\text{eV}$ (from tritium decay).

False vacuum beyond standard model related to neutrino structure will not be perturbed by nuclear size strong fields, it needs micrometer sized-multi-wavelength strong fields to be perturbed.

Vacuum quench by by QED Field, size scale micron

Recall: $\hbar c = 197\,\mathrm{MeV\,fm} = 197\,\mu\,\mathrm{meV}$

$$L = 2\pi \frac{\hbar c}{m_\nu} = 1\mu\mathrm{m} \quad \text{for } m_\nu = 1.24\,\mathrm{eV}$$

Strong (laser) fields at micron scale can be man-made and could help quench the vacuum in particular if scale of dark energy $\lambda = 100$ meV^4 and neutrino mass, $\Delta m_{12} = 8.9$meV and $\Delta m_{13} = 49$meV are related. Absolute neutrino mass scale not known but $m_{1,2,3} < 2$eV (from tritium decay).

False vacuum beyond standard model related to neutrino structure will not be perturbed by nuclear size strong fields, it needs micrometer sized-multi-wavelength strong fields to be perturbed.

Vacuum quench by by QED Field, size scale micron

Recall: $\hbar c = 197\,\mathrm{MeV\,fm} = 197\,\mu\,\mathrm{meV}$

$$L = 2\pi \frac{\hbar c}{m_\nu} = 1\mu\mathrm{m} \quad \text{for } m_\nu = 1.24\,\mathrm{eV}$$

Strong (laser) fields at micron scale can be man-made and could help quench the vacuum in particular if scale of dark energy $\lambda = 100$ meV^4 and neutrino mass, $\Delta m_{12} = 8.9$meV and $\Delta m_{13} = 49$meV are related. Absolute neutrino mass scale not known but $m_{1,2,3} < 2$eV (from tritium decay).

False vacuum beyond standard model related to neutrino structure will not be perturbed by nuclear size strong fields, it needs micrometer sized-multi-wavelength strong fields to be perturbed.

Conclusion: We are back to the æther

Albert Einstein rejected æther ('vacuum') as unobservable when formulating special relativity, but he changed his initial position, re-introducing what is referred to as the 'relativistically invariant' æther.

In a letter to H.A. Lorentz of November 15, 1919, see page 2 in *Einstein and the Æther*, L. Kostro, Apeiron, Montreal (2000).

he writes:

It would have been more correct if I had limited myself, in my earlier publications, to emphasizing only the non-existence of an æther velocity, instead of arguing the total non-existence of the æther, for . . . I can see that with the word æther we say nothing else than that space has to be viewed as a carrier of physical qualities.

6 months later in a lecture published in May 1920 in Berlin by Julius Springer, in Einstein collected works lecture (given on 27 October 1920 at Reichs-Universität zu Leiden, addressing H. Lorentz) *æther may not be thought of as endowed with the quality characteristic of ponderable media, as consisting of parts which may be tracked through time. The idea of motion may not be applied to it.*