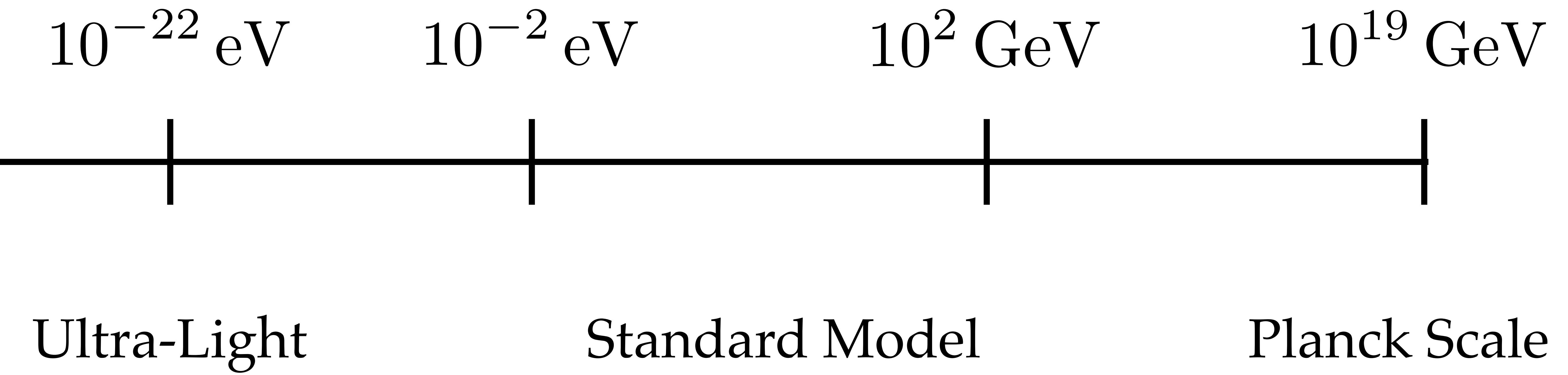
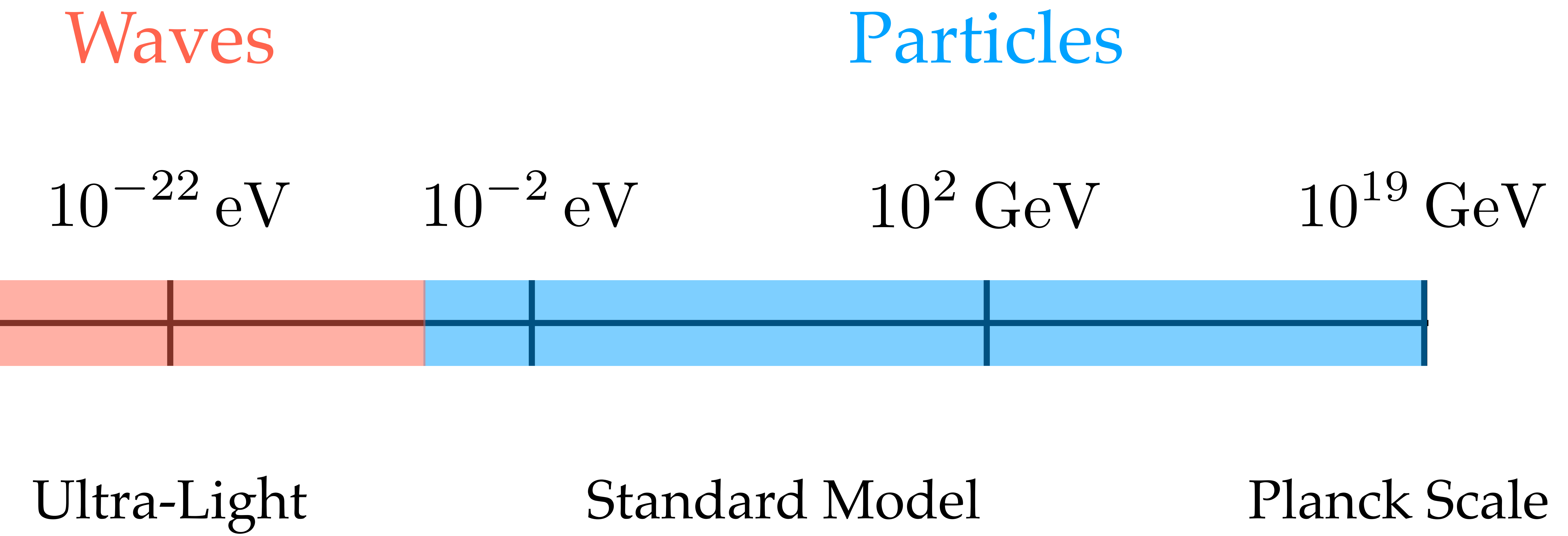
New ideas in the realm of ultra-light BSM theory and phenomenology

Anson Hook
University of Maryland

Ultra-Light particles



Ultra-Light Waves



Wave - Particle duality

- Particles
  - Heavy
  - Can see individual quantua
  - Produce few

- Waves
  - Light
  - Cannot see/distinguish individual quanta
  - Produce many
  - Ultra-light : Human time/length scales

Why new ultra-light states?

Experimentally

We have seen ultra-light fields before, why not again?

Theoretically

String theory/extra dimensions generically predicts many many light particles that are exponentially light

Theory of ultra-light scalars

Production Mechanism

Misalignment and string production

Model Building

Theory of mass and coupling
non derivative scalar interactions

Theory of ultra-light scalars

Caveat : non-derivative scalar interactions

Theoretically : ultra-light scalars are characterized by two competing effects

Strong coupling   low mass

Strong coupling implies large potential energy
Large potential energy implies a large mass $E = mc^2$

$$m^2_{\rm obs} = m^2_{\rm bare} + V$$

Theory of ultra-light scalars

$$m_{\text{obs}}^2 = m_{\text{bare}}^2 + V$$

Unless there is fine-tuning involved, need a theory for this cancelation

Why are cancelations bad?

Experiment : dimensional analysis

Fun Fact : Perpetual Motion machines

Theory of ultra-light scalars

Unfortunately, only one model of light scalars

Z_N discrete symmetry

PNGBs of Z_N

Start with a NGB of a U(1)

$$\frac{\phi}{f} = 2\pi + \frac{\phi}{f}$$

Make it non-linearly realize a Z_N symmetry

$$\frac{\phi}{f} \to \frac{\phi}{f} + \frac{2\pi}{N} \qquad V(\frac{\phi}{f}) = V(\frac{\phi}{f} + \frac{2\pi}{N})$$

PNGBs of Z_N

Any potential for this PNGB can be written as

$$V(\phi) \propto \sum_{k=0}^{N-1} F(\frac{\phi}{f} + \frac{2\pi k}{N})$$

Written in this form, if F is independent of N, then this is a Riemann Sum!

PNGBs of Z_N

$$V(\phi) \propto \sum_{k=0}^{N-1} F\left(\frac{\phi}{f} + \frac{2\pi k}{N}\right) = \frac{N}{2\pi}\int_0^{2\pi} F(\theta)d\theta + \mathcal{O}(N^0)$$

Large N limit is independent of the PNGB

Expected since as N goes to infinity, you have a continuous shift symmetry

Convergence Theorems

Riemann sums have a lot of theorems associated with them

$$E_N(F) = \int_0^{2\pi} F(\theta) d\theta - \frac{2\pi}{N} \sum_{k=0}^{N-1} F(\frac{\phi}{f} + \frac{2\pi k}{N})$$

The potential for the PNGB comes entirely from the error in the Riemann sum in approximating an integral

Euler-Maclaurin Theorem

If the function F is analytic

Then there is a strip around the real axis from -i a to i a
where F is a holomorphic function with a bound M

$$|E_N(F)| \leq \frac{4\pi M}{e^{Na} - 1}$$

Well behaved potentials where no particle becomes massless result in exponentially suppressed PNGB masses

Tuned axions

Consider N decoupled QCDs all coupled to the same PNGB axion

QCDs exchange under Z_N

$$G_k \to G_{k+1}$$

Axion non-linearly realizes the Z_N

$$\frac{a}{f} \to \frac{a}{f} + \frac{2\pi}{N}$$

Tuned axions

Leading order coupling between the various sectors

$$\sum_k \frac{g^2}{32\pi^2}\left(\frac{a}{f}+\frac{2\pi k}{N}+\theta\right) G_k \tilde{G}_k$$

Each sector gives a potential of the form

$$V = -m_\pi^2 f_\pi^2 \sqrt{1-\frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{\bar{\theta}-a/f_a}{2}\right)}$$

Tuned axions

Total potential is the sum

$$V(a) = -\ m_\pi^2 f_\pi^2 \sum_k \sqrt{1 - 4\frac{m_u m_d}{(m_u + m_d)^2}\sin^2\left(\frac{a}{2f} + \frac{\pi k}{N}\right)}$$

Potential is analytic

Mass should be exponentially suppressed

Tuned axions

$$V(a) \sim \sqrt{\frac{m_d - m_u}{\pi N (m_d + m_u)}} (-\frac{m_u}{m_d})^N m_\pi^2 f_\pi^2 \cos\left(\frac{Na}{f}\right)$$

Axion mass can naturally be exponentially lighter than the normal QCD contribution!

Phenomenology of ultra-light scalars

Ultra light scalars have interesting phenomenology, most of it tied with its apparent fine tuned nature

Changing values of fundamental constants

Unique cosmology

Fifth forces

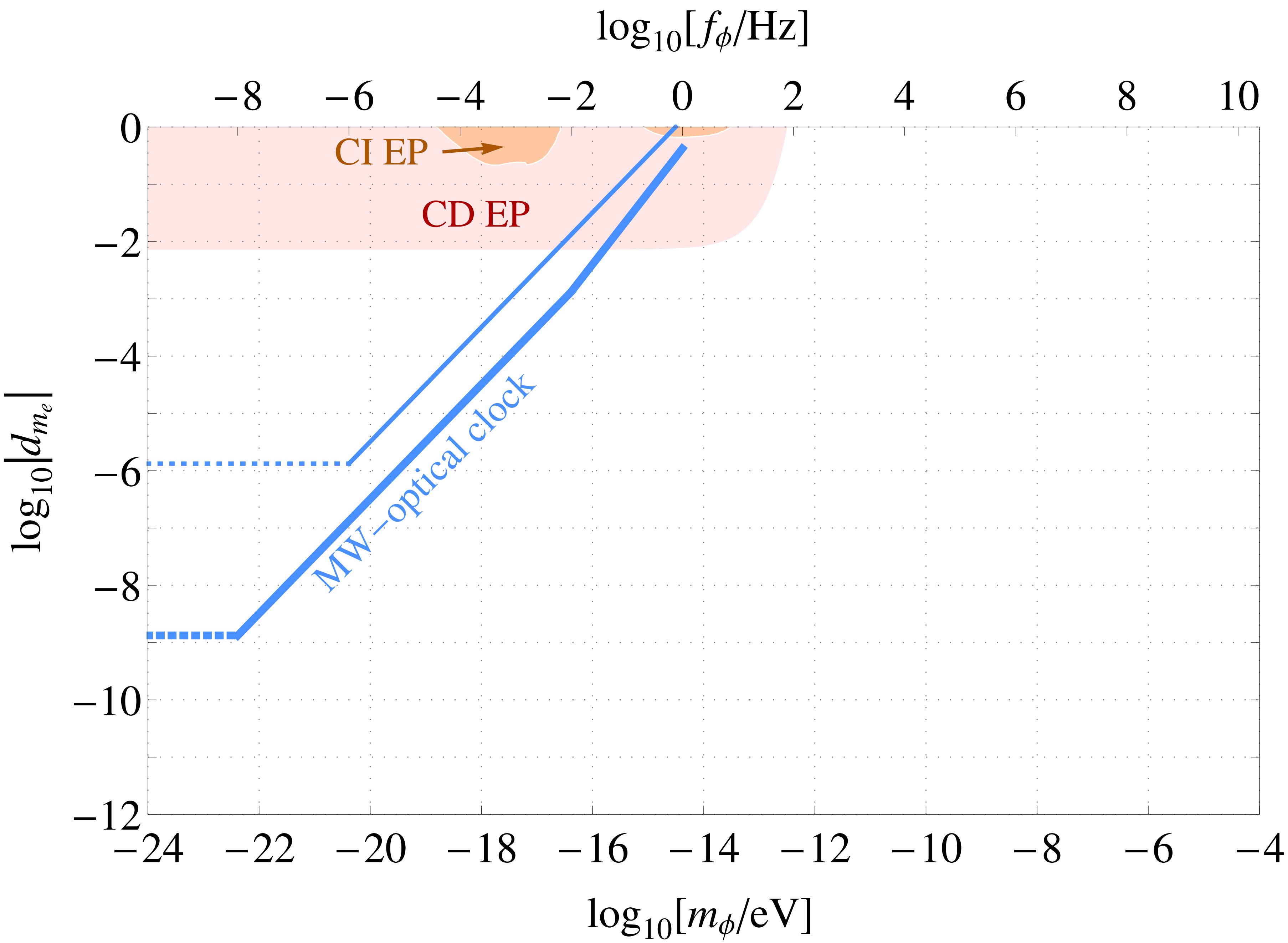
Fundamental "Constants"

$$\mathcal{L} \supset \left(d_{m_e} \frac{\phi}{M_{pl}} + m_e \right) \bar{e} e$$

Scalar changes mass of the electron

Source		Detector
Dark Matter	Time dependence	Atomic/Molecular/
Heavy Body	Space dependence	Nuclear Transitions

Fundamental "Constants"



hep-ph / 1405.2925

Unique Cosmology

$$\delta V = |d_{m_e}\frac{\phi}{M_{pl}} + m_e| n_e$$

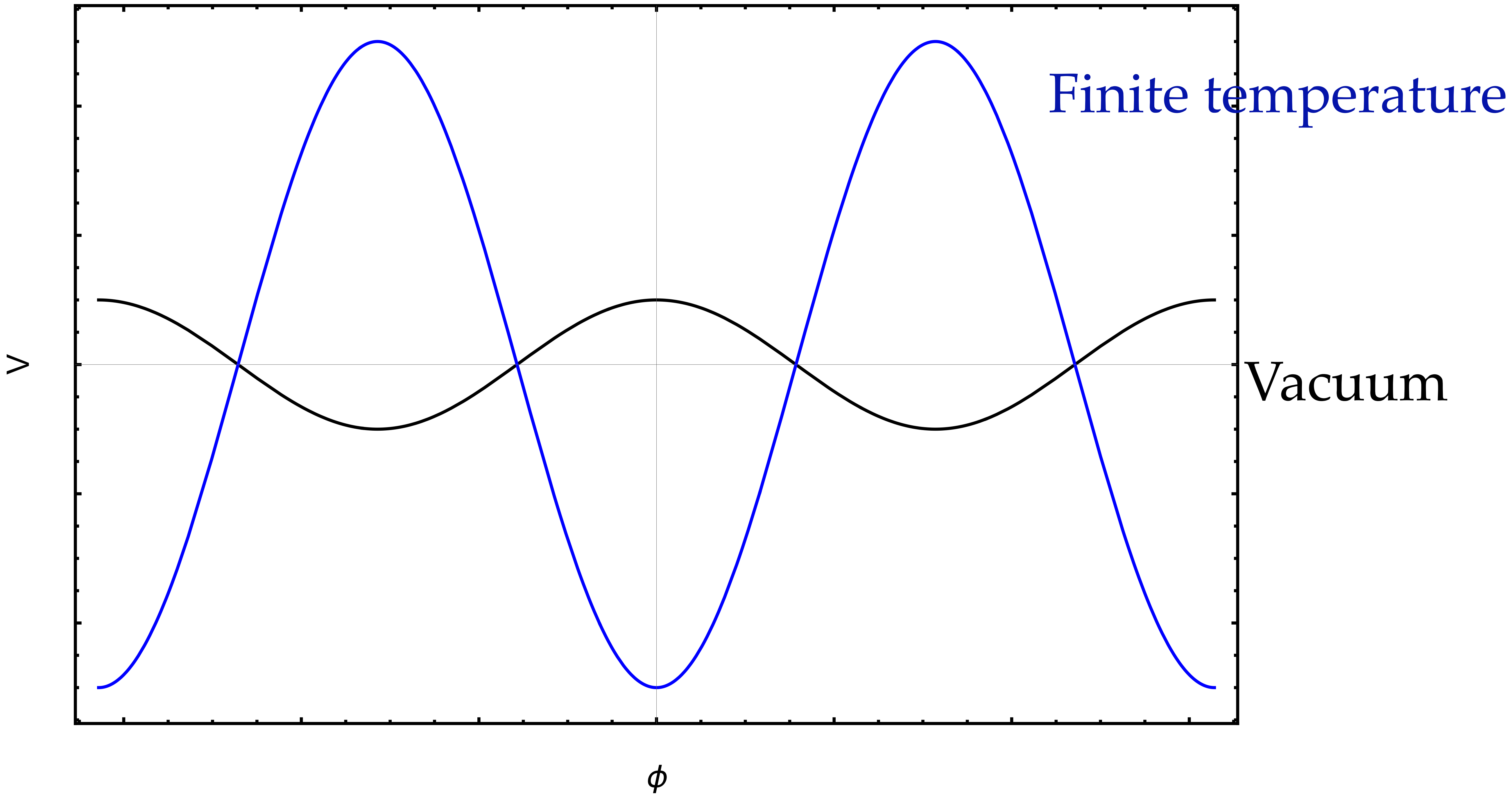
Finite density

$$\delta V \propto (d_{m_e}\frac{\phi}{M_{pl}} + m_e)^2 T^2$$

Finite temperature

Being fine-tuned means that finite density/ temperature effects are more important than your vacuum potential

Unique Cosmology



Unique Cosmology

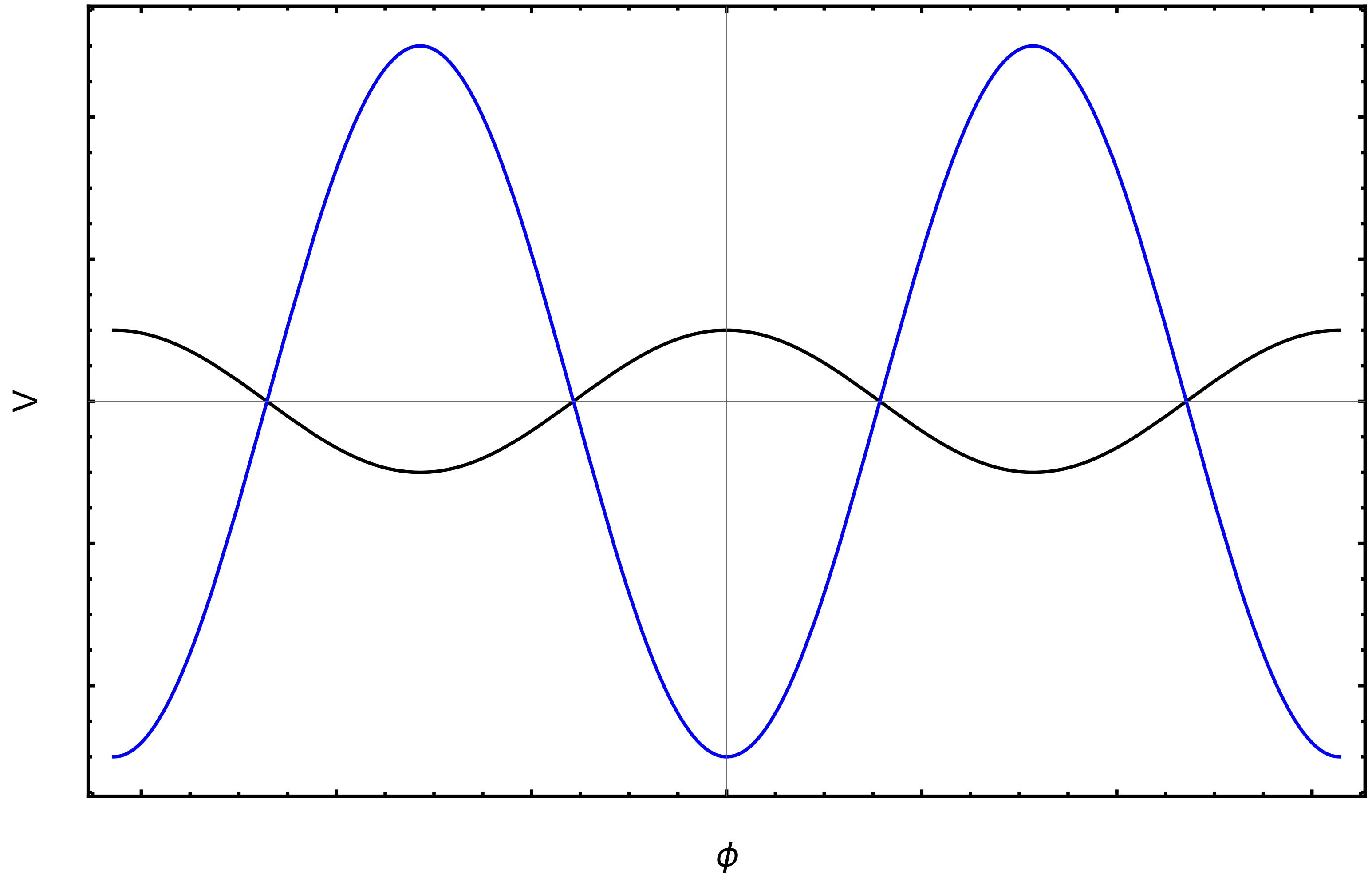
Consequence of starting near maximum

Enhanced structure formation in the form of minihalos

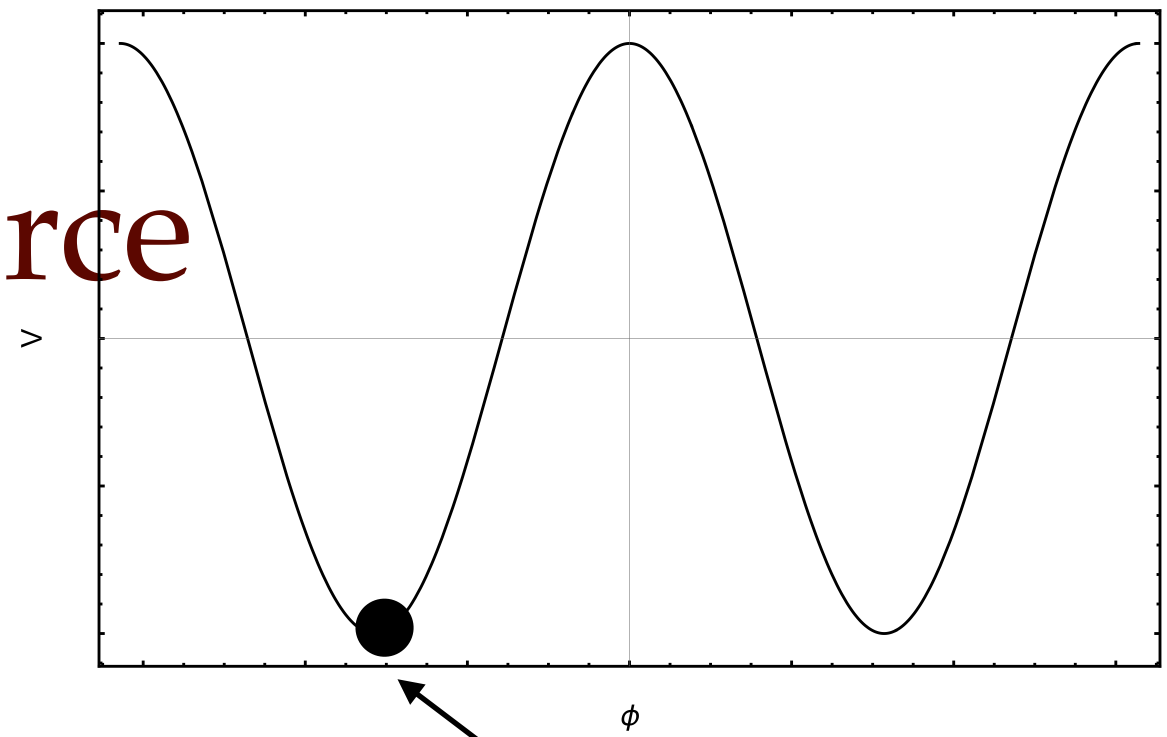
Large change in the abundance calculation

Fifth Force

Tuning/finite density effects change fifth force bounds greatly

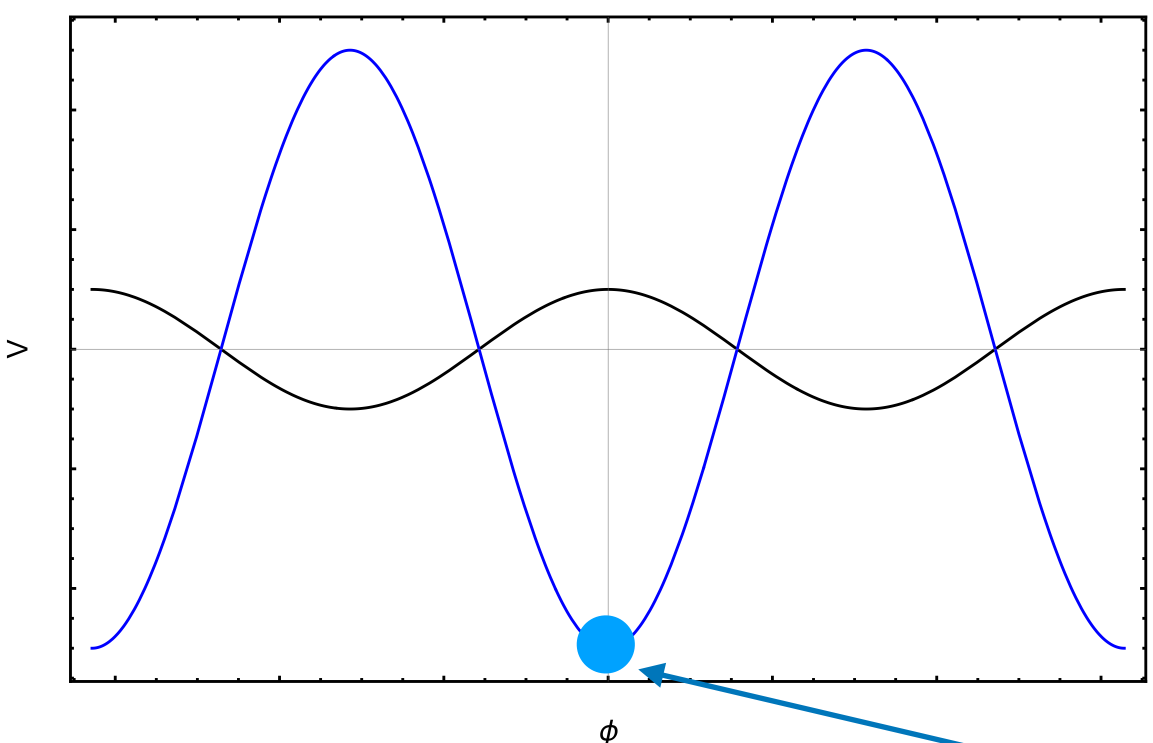


Fifth Force



Relax to vacuum minimum
away from source

Star / Planet



Finite density max
aligned with vacuum min

Sitting at finite density minimum

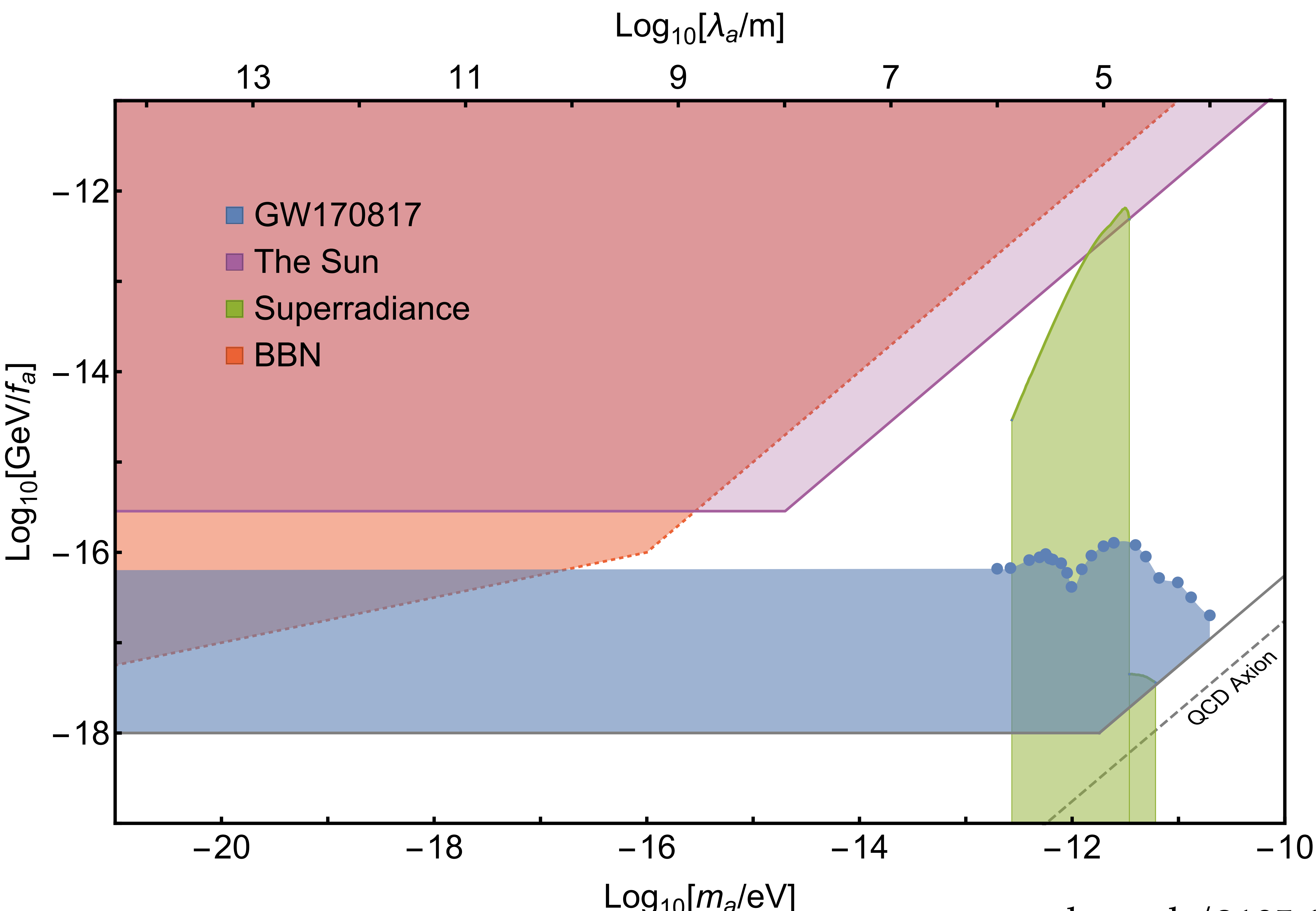
Fifth Force - Neutron Stars

Neutron stars can source axion mediated fifth forces

Visible only at LIGO

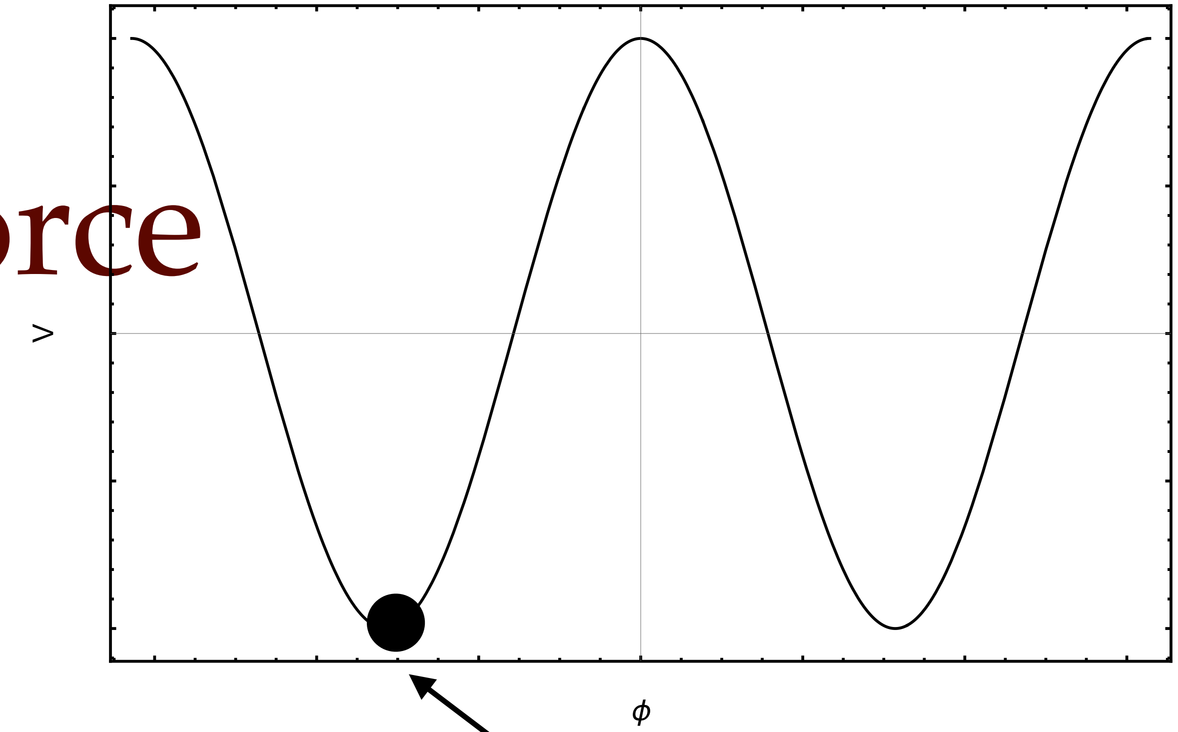
No fifth force from other experiments!
- Spontaneous Scalarization

Fifth Force - Neutron Stars



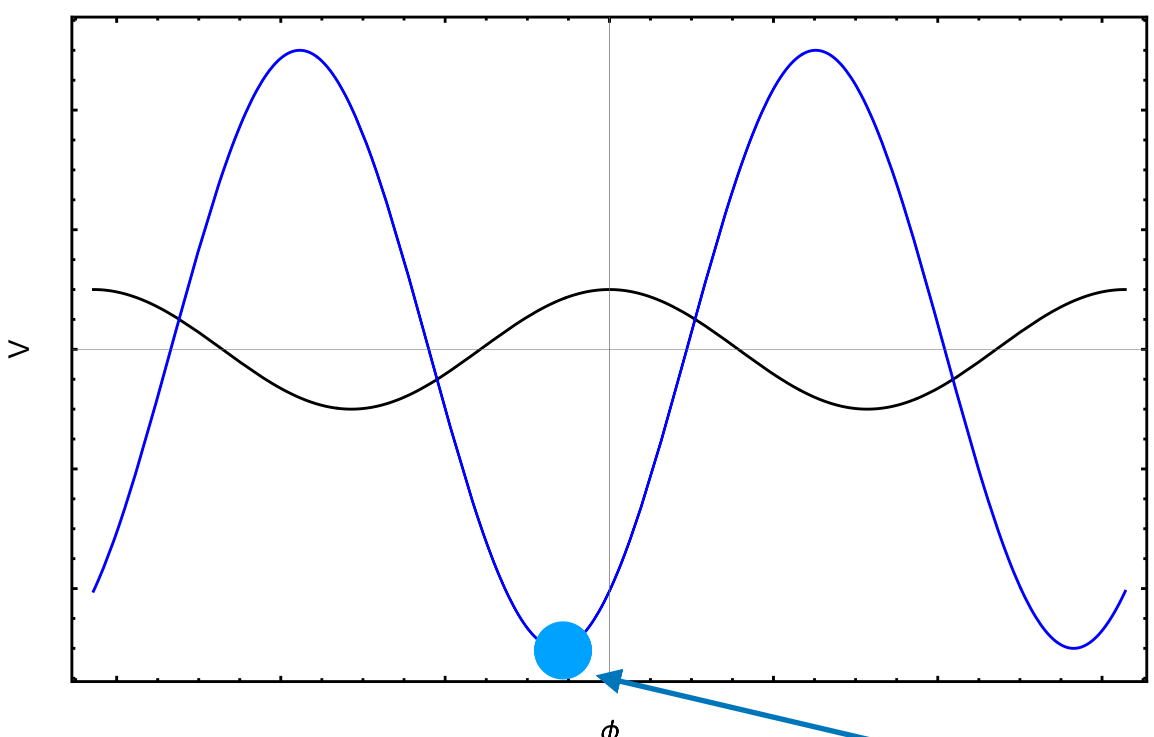
hep-ph/2105.13963

Fifth Force



Relax to vacuum minimum away from source

Star/Planet



Finite density max mis-aligned with vacuum min

Sitting at finite density minimum

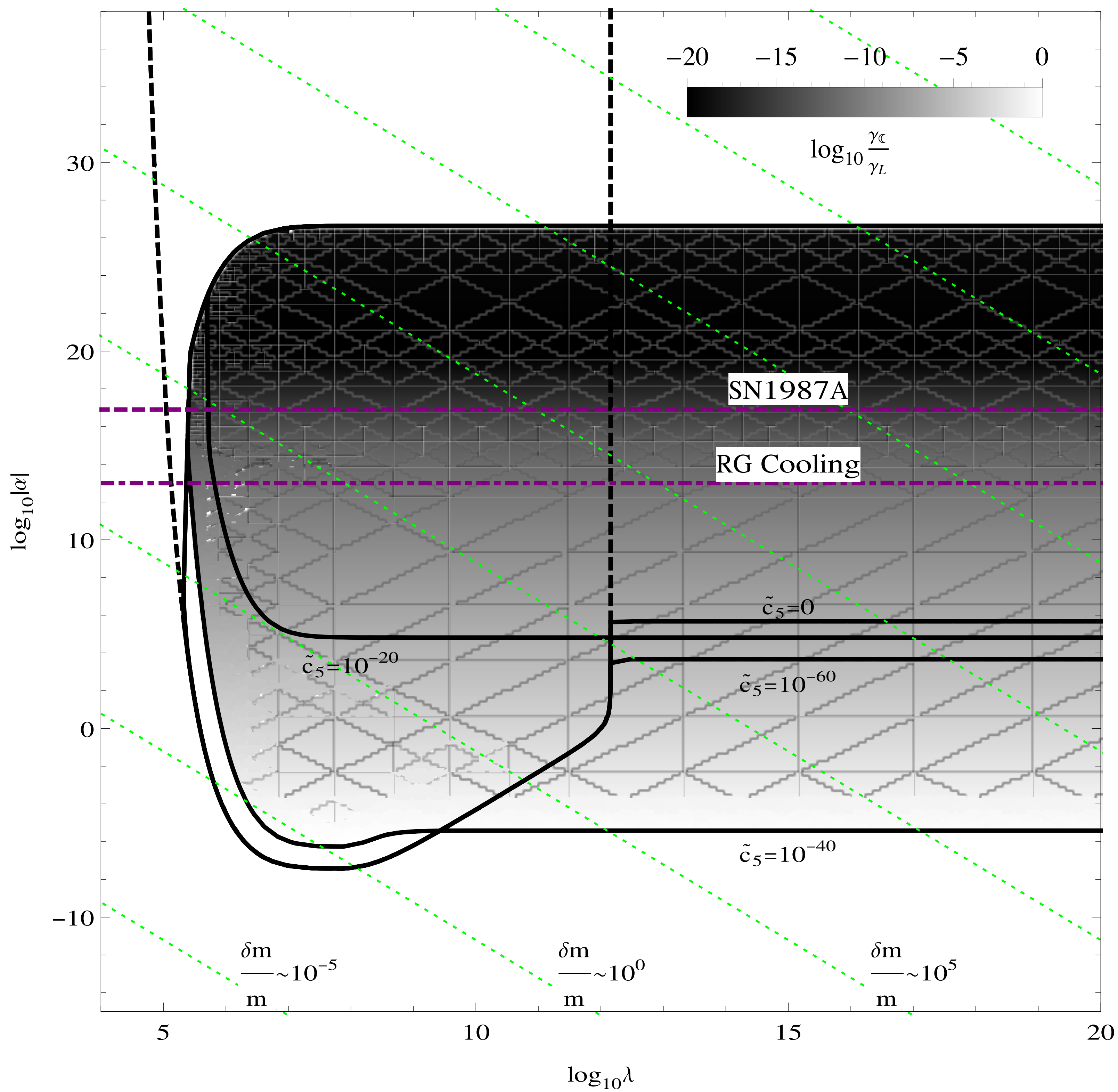
Fifth Force - Chameleons

Constant vev inside of the earth

No-fifth force present for earth based experiments

Capacitor like phenomenology

Fifth Force - Chameleons



Conclusion

Ultra-light scalars and an interesting subject

Theory

Fine-tuning / failure of dimensional analysis

Only one model

Good thing, opportunity!

Experiment

Sensitivity to finite density and temperature

Fifth Force, Cosmology, Non-constant constants of nature