Relaxing the Cosmological Constant and Dark Energy Radiation

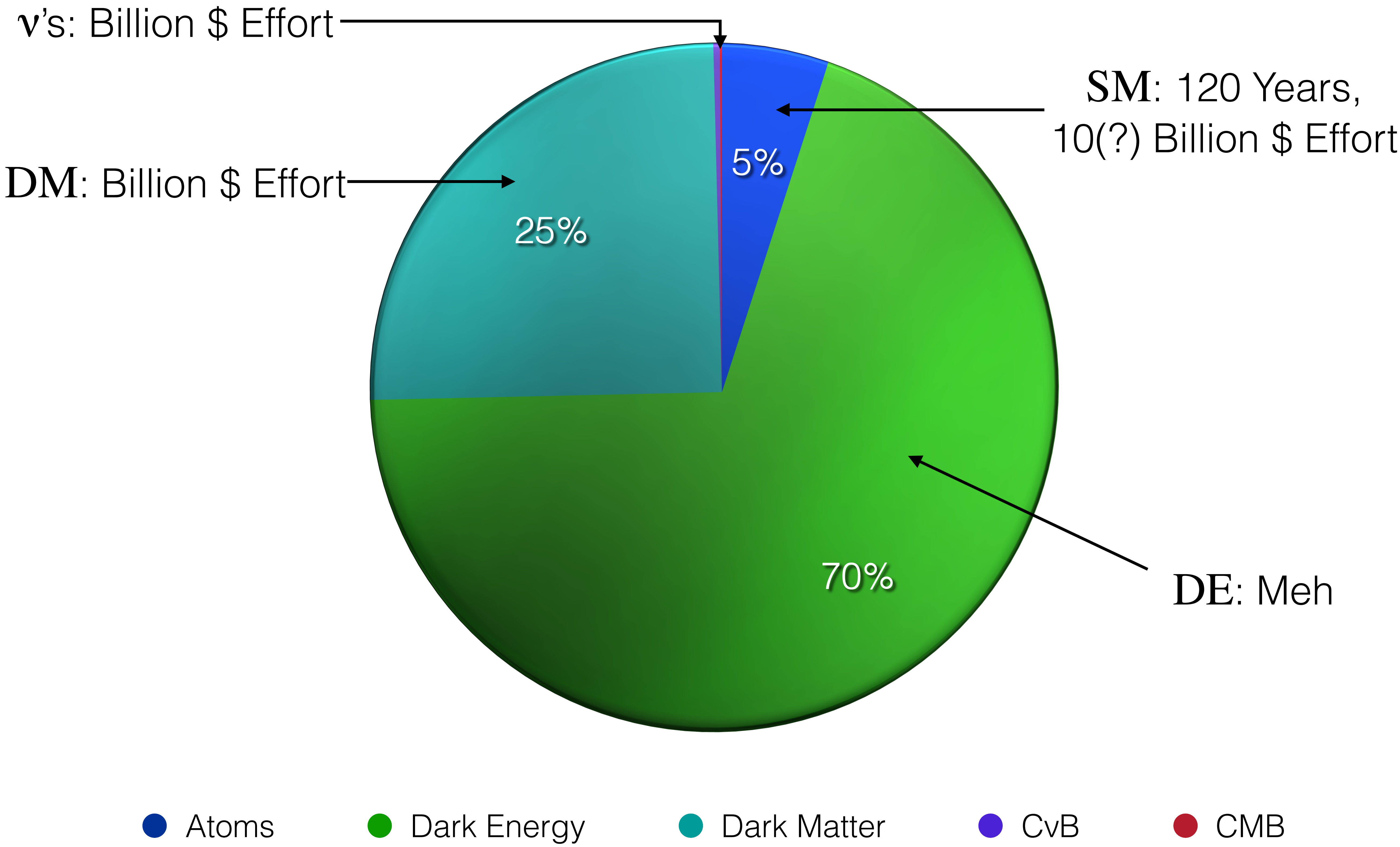
with K Berghaus, P Graham, G Moore, S Rajendran - 2012.10549

with P Graham, S Rajendran - 1902.06793, 1709.01999

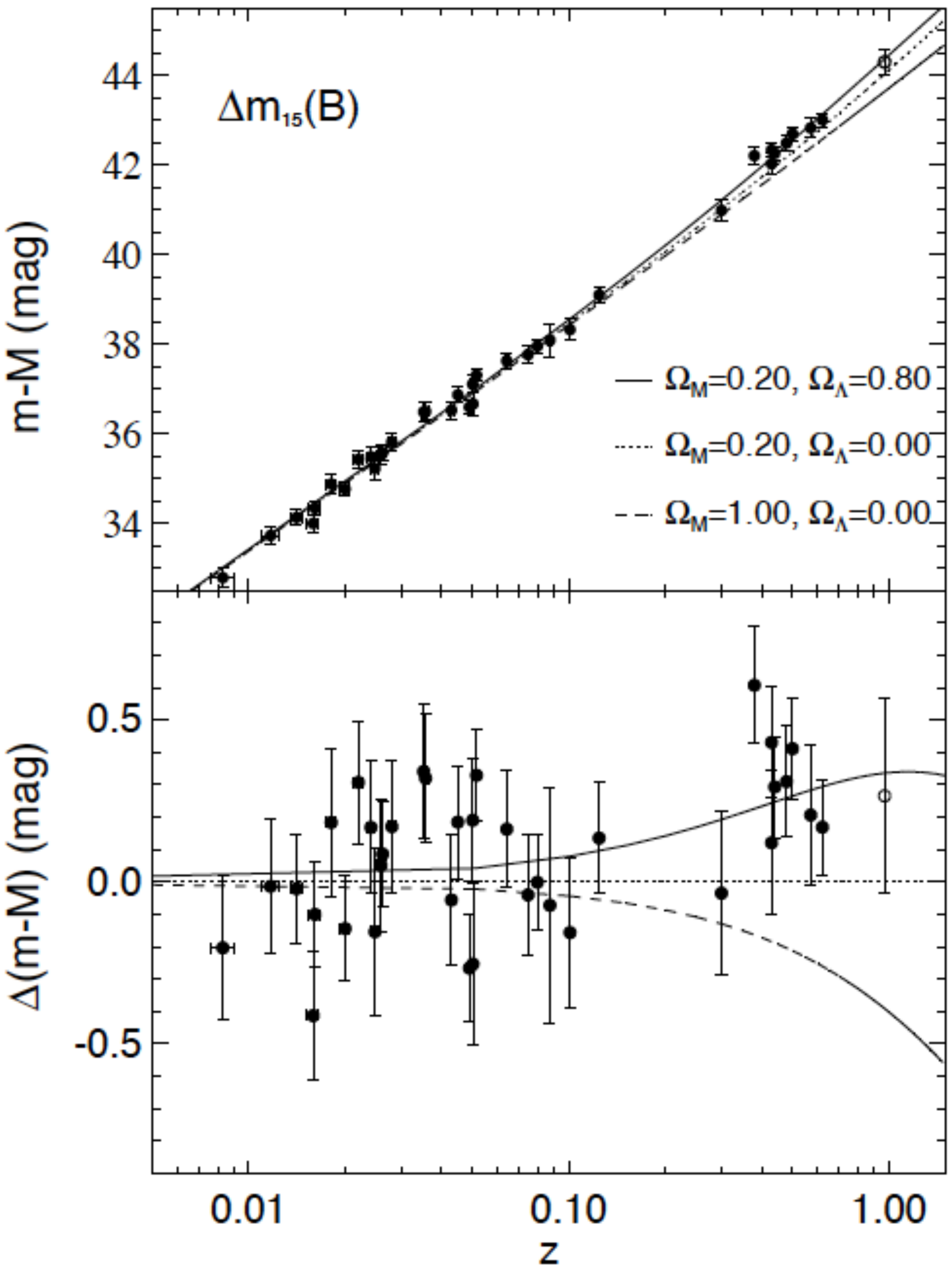
with P Graham, S Haciömeroğlu, Z Omarov, S Rajendran, Y Semertzidis - 2005.11867

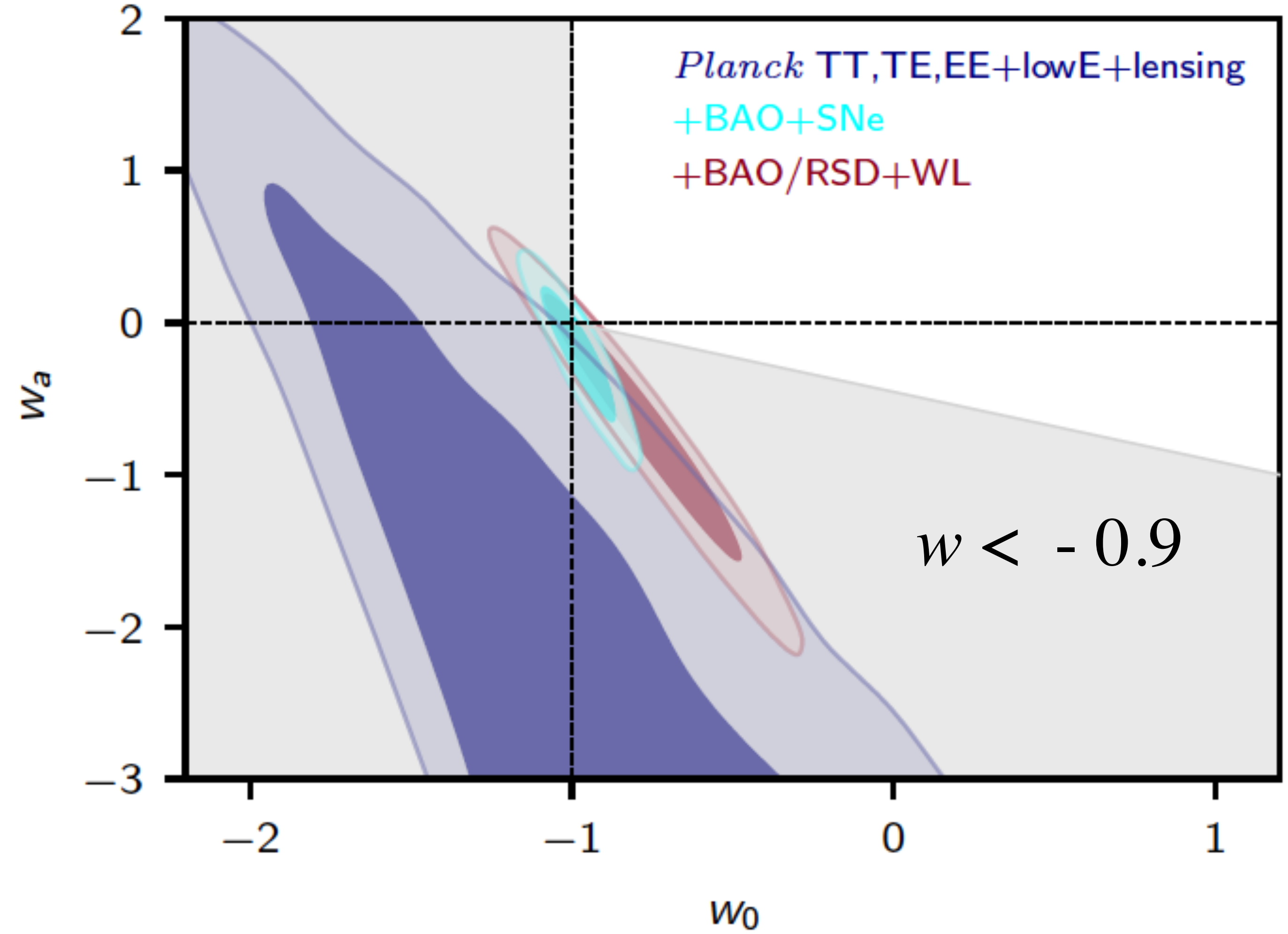
Microscopic Details of the Universe

The Universe Today



Dark Energy: EOS?





$$w \equiv p/\rho$$

Cosmological constant: w = -1

Anything else, there are dynamics.

Laboratory Probes of Dark Energy?

Theory bias: $w = -1$

$$-1 \leq w \leq -0.95$$

Gravitational measurement. Can we do better in the lab?

Dark Matter

Similar to laboratory detection of dark matter issues —

Gravitational Measurements: dark matter is a cold, pressureless gas with $\sigma/m < \mathrm{cm}^2/\mathrm{g}$

Does not mean $\sigma = 0$. Can probe $\sigma \sim 10^{-49}\ \mathrm{cm}^2$ in the lab

What are the signatures of dark energy?

Assumption: Cosmological Constant

$$\int d^4x\sqrt{-g}(M_{pl}^2 R + \mathcal{L}(\phi_{sm}, \partial\phi_{sm}) + \Lambda_0)$$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{1}{M_{pl}^2}(T_{\mu\nu} + g_{\mu\nu}\Lambda)$$

$$T_{\mu\nu} = \mathrm{diag}(\rho, p, p, p)$$

$$H^2 = \frac{1}{3M_{pl}^2}(\rho + \Lambda)$$

$$\dot{H} = -\frac{1}{2M_{pl}^2}(\rho + p)$$

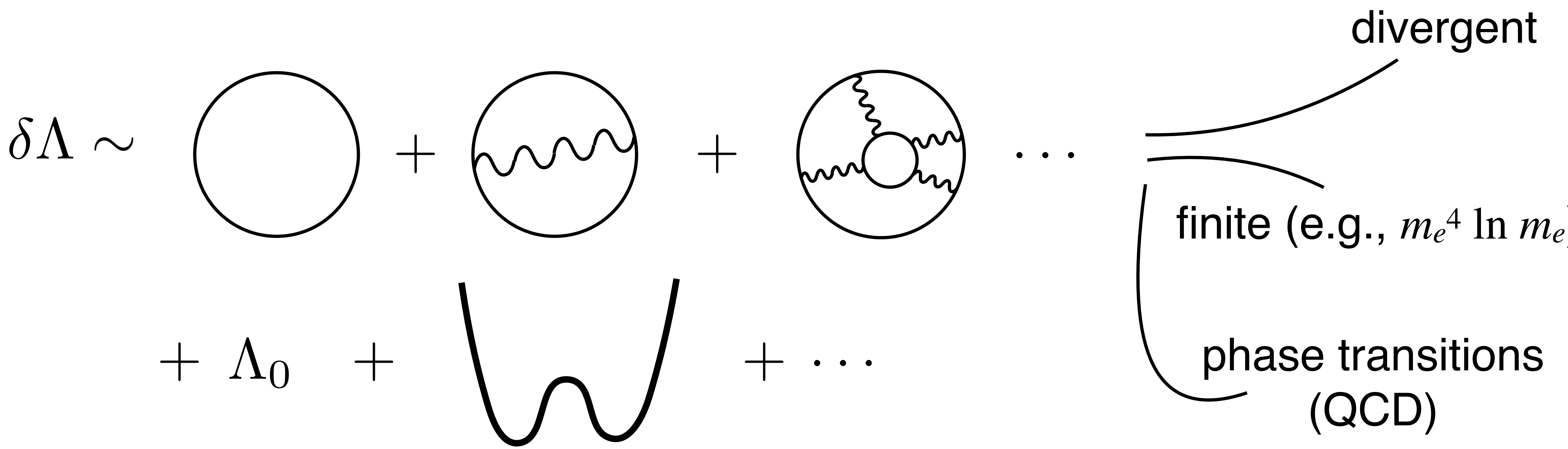
CC is time-independent (normal matter redshifts).

CC-dominated spacetime grows exponentially fast.

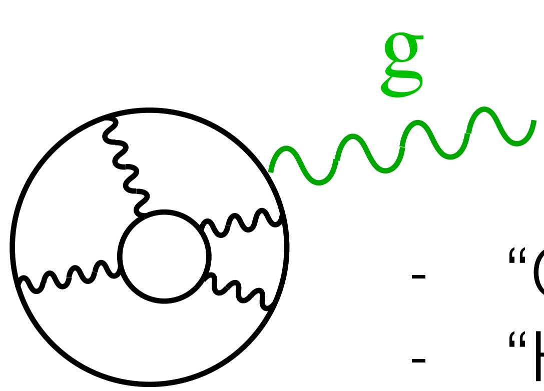
$$a = a_0 e^{Ht}$$

CC Contributions

The delicateness of the cosmological constant.

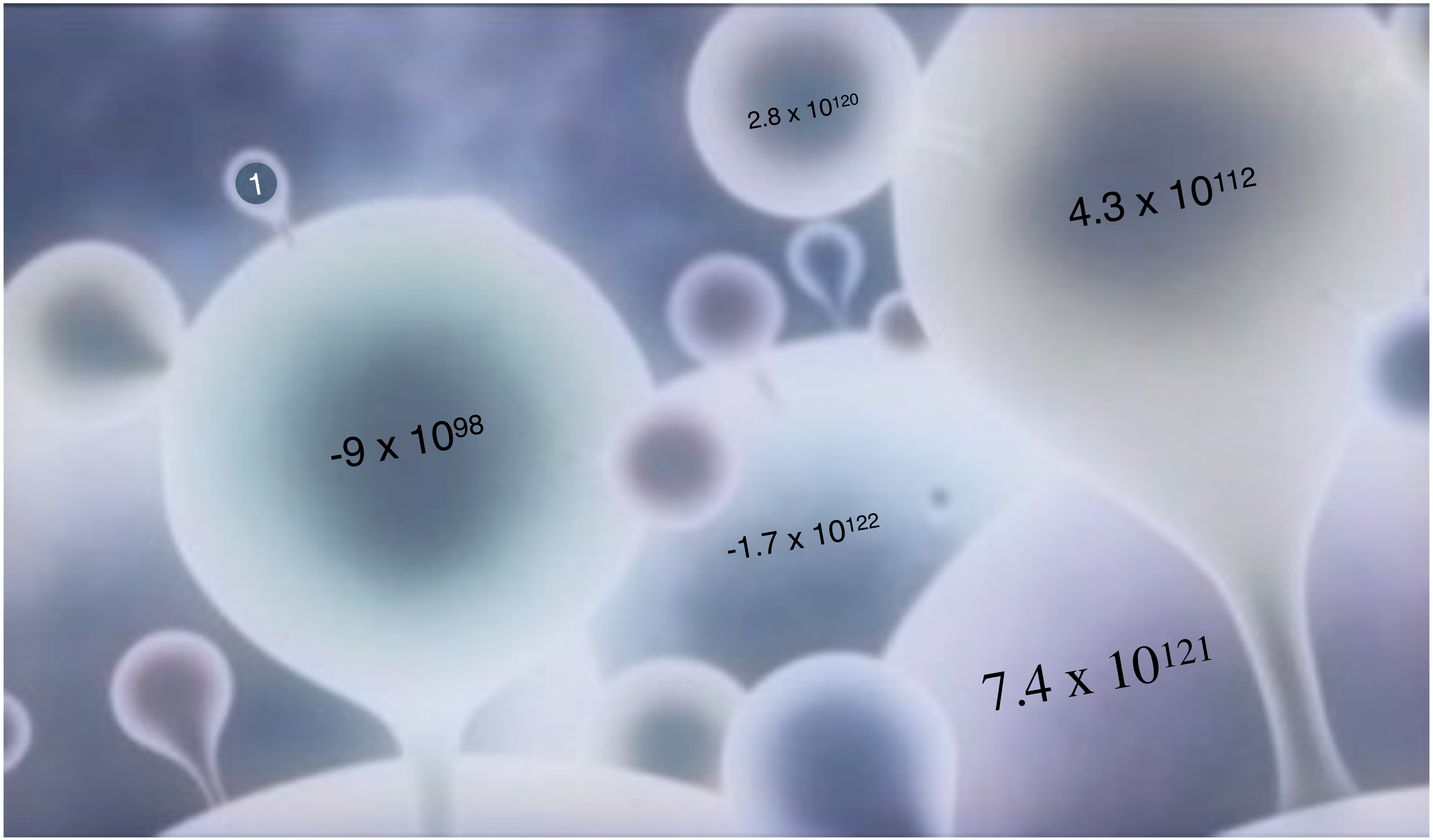


$\text{Naive}: M_{pl}^4 \sim 10^{123} \rho_{D.E.}$



- “Quantum gravity is weird…” (not at low energies)
- “How can you calc. when you are in curved space…” ($R << \Lambda$)
- “UV/IR dude…” (well that’s the problem)

Explanation: It's Anthropic



Structure only forms when CC is tiny… (assumes given $\delta\rho/\rho$)

A 'historical' solution

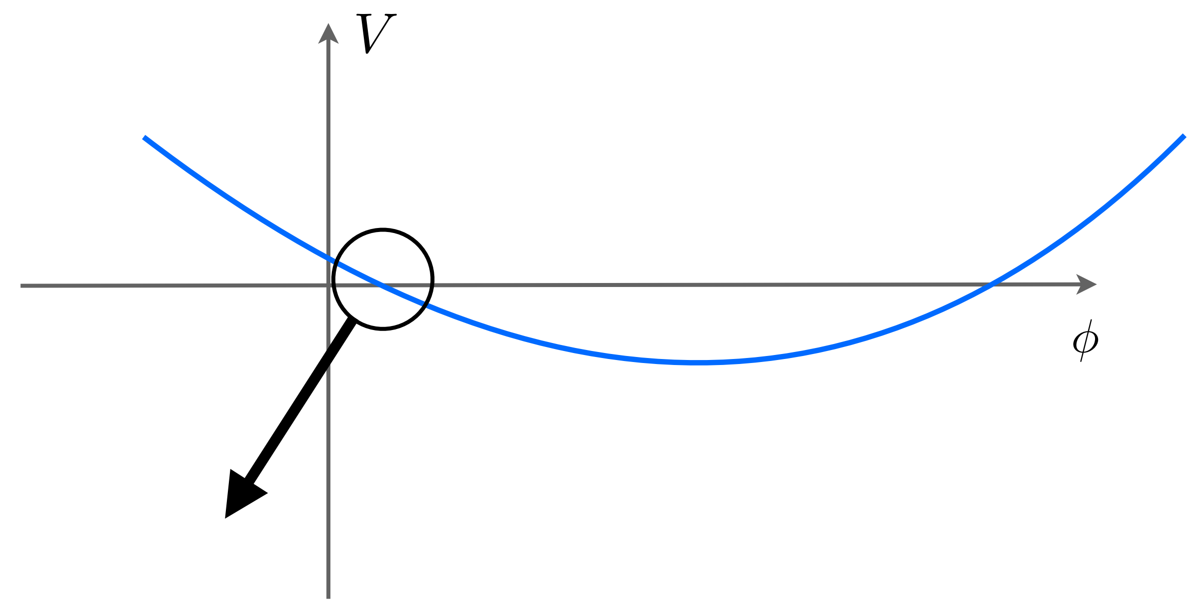
Outline

I. CC Solution - Rolling field

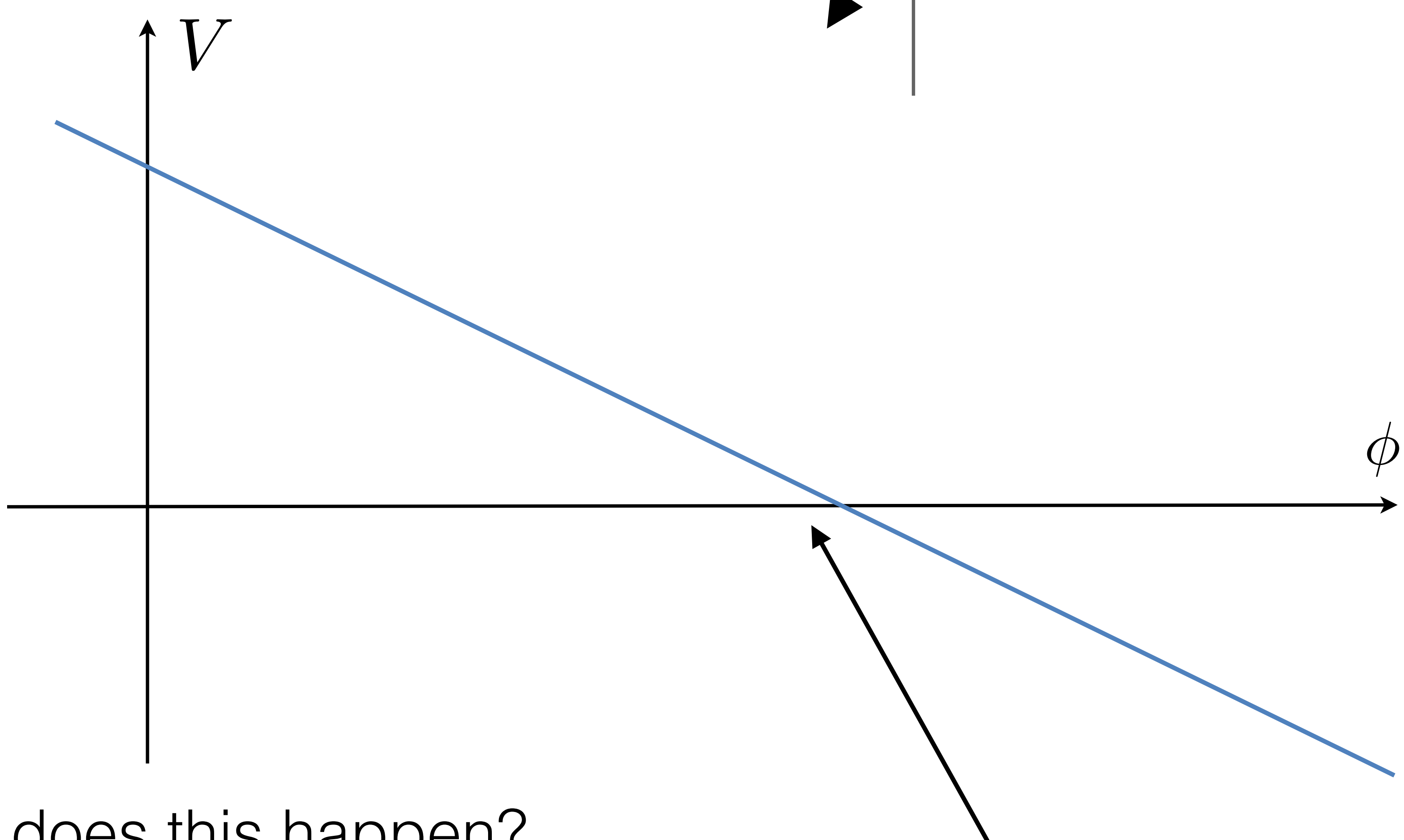
II. Models of Dark Energy

III. Detection of Dark Energy

Scan the CC with a light field



Must scan a large range of values!

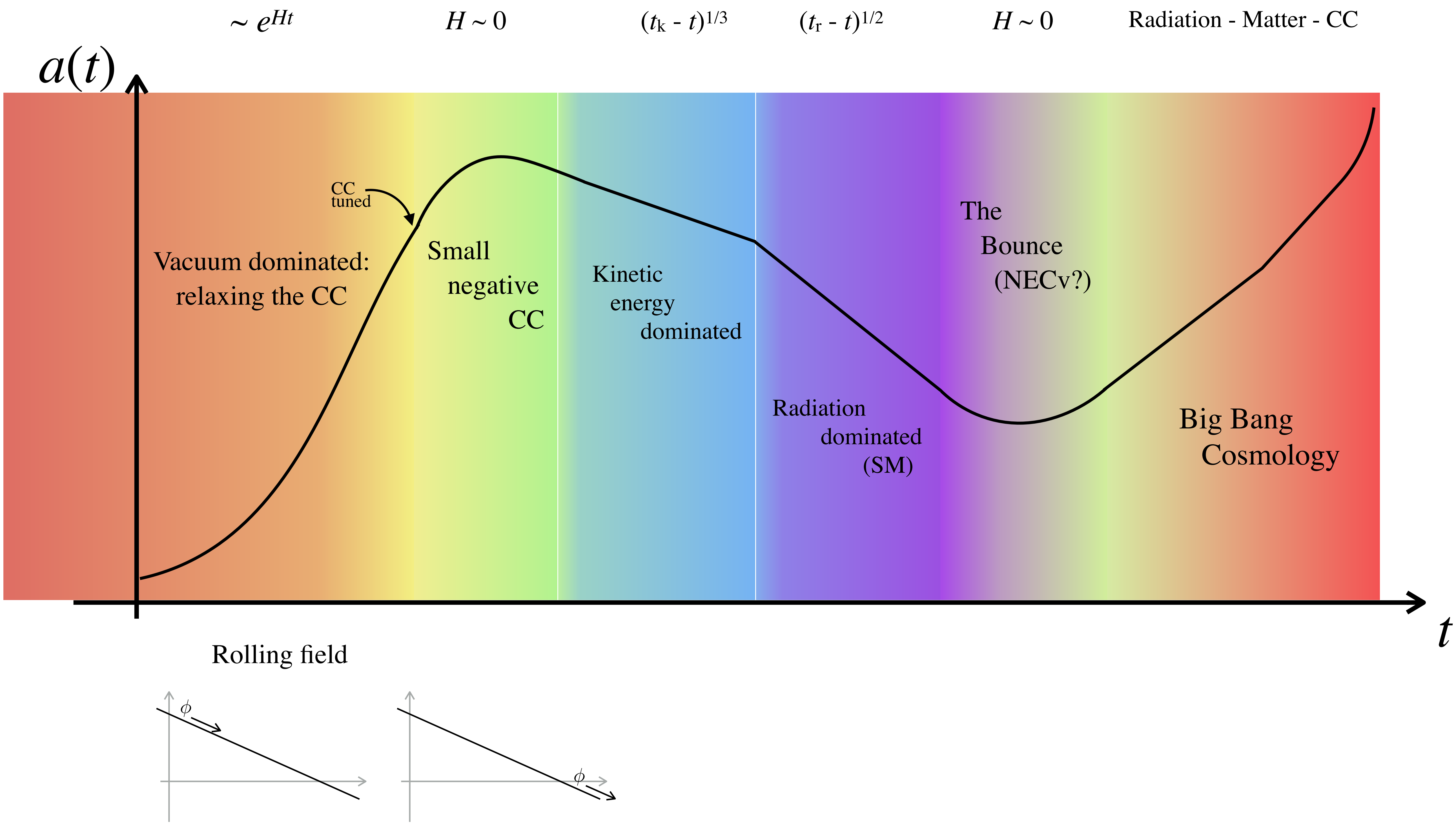


When does this happen?

Why are we here?

Our Model: Summary

Evolution of the scale factor

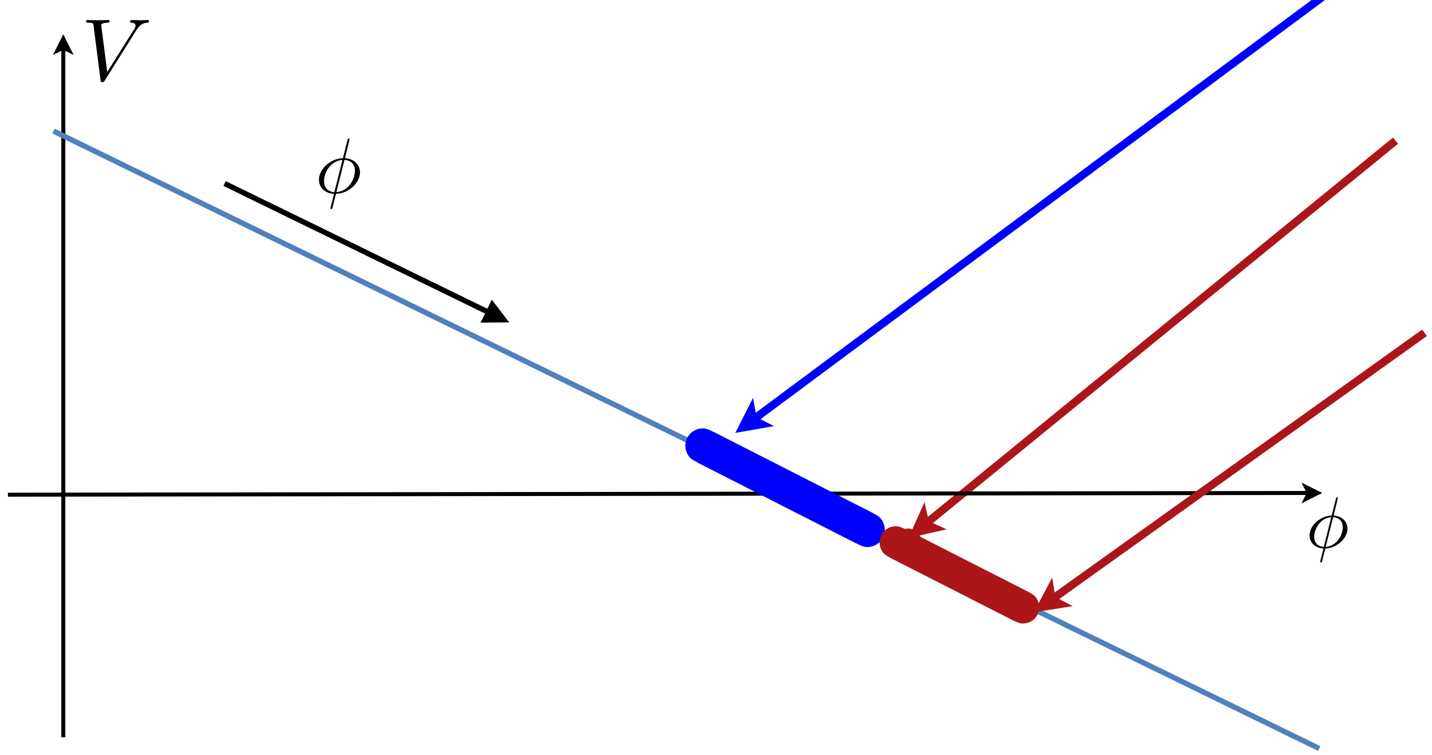


Our Model: Summary

Evolution of the rolling scalar field

Simplest Model:

$$\mathcal{L} \supset g^3\phi + \text{arbitrary CC}$$



- ϕ slow rolls (extremely long time), CC drops
- Critical point: at $\phi \sim M_{pl}$, ϕ fast rolls through zero, universe starts to crunch
- Kinetic energy blue-shifts as universe crunches
- Reheating: kinetic energy converted to radiation, ϕ is stopped
- Bounce occurs, regular post-inflation cosmology afterwards
- High Hubble scale freezes ϕ until today, CC fixed at small value (set by g)

CC Solution: Initial Expansion

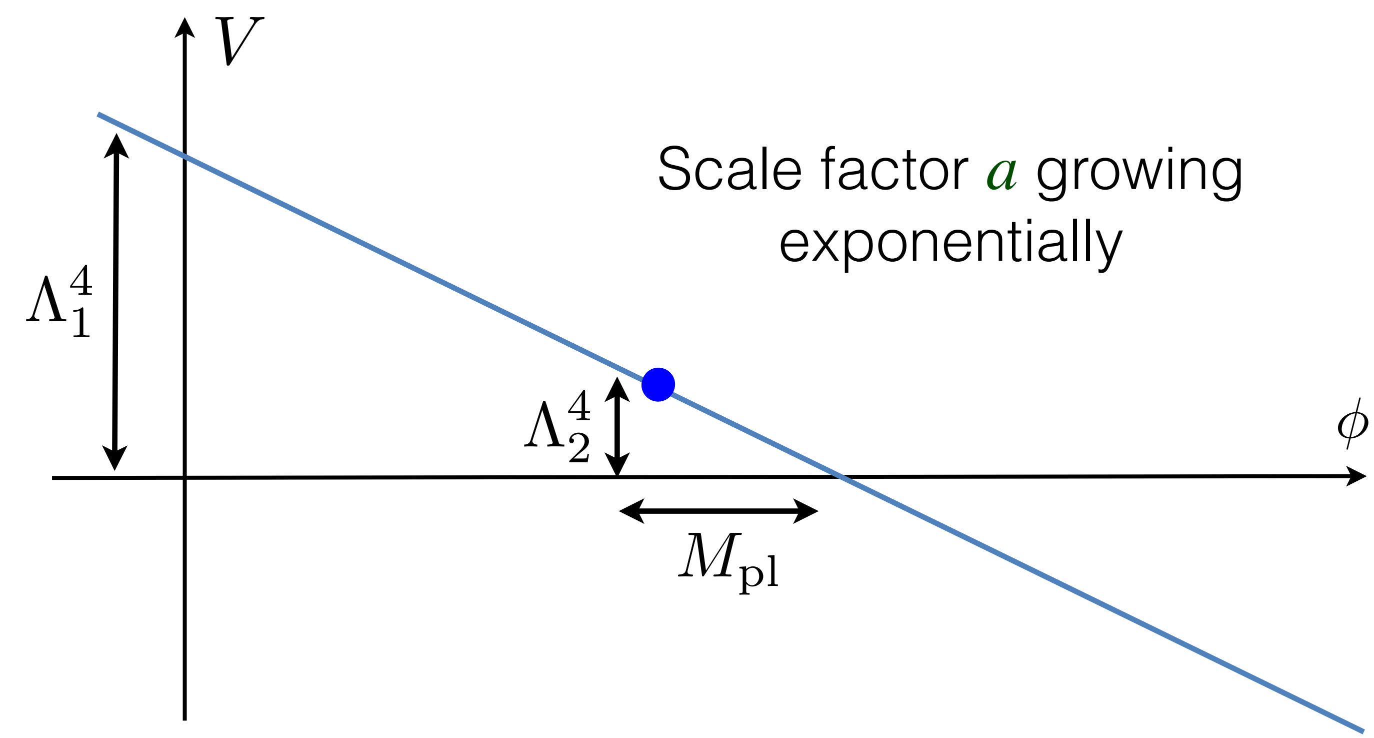
Simplest Model: $\mathcal{L} \supset g^3\phi + \text{arbitrary CC} + \frac{\phi}{f}F'\tilde{F}' + \frac{\phi}{f_G}G'\tilde{G}'$

Avoid eternal inflation at top:

$$H^3 \lesssim V' \;\rightarrow\; g \gtrsim \frac{\Lambda_1^2}{M_{\rm pl}}$$

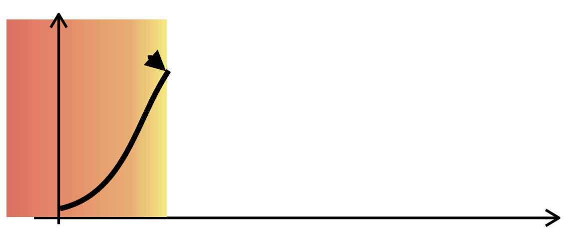
Fast roll begins: $g^3 M_{\rm pl} \sim \Lambda_2^4$

Together ➜ $\boxed{\Lambda_1^3 \lesssim \Lambda_2^2\, M_{\rm pl}}$



So to get today's CC $\Lambda_2 \sim \text{meV}$, can solve the CC problem up to $\Lambda_1 \sim 10\ \text{MeV}$
— more fields, higher initial scale

Dynamical relaxation first tried by Abbott (1985) and Banks (1984).
Suffered from eternal inflation and an empty universe.



CC Solution: Roll to Negative CC

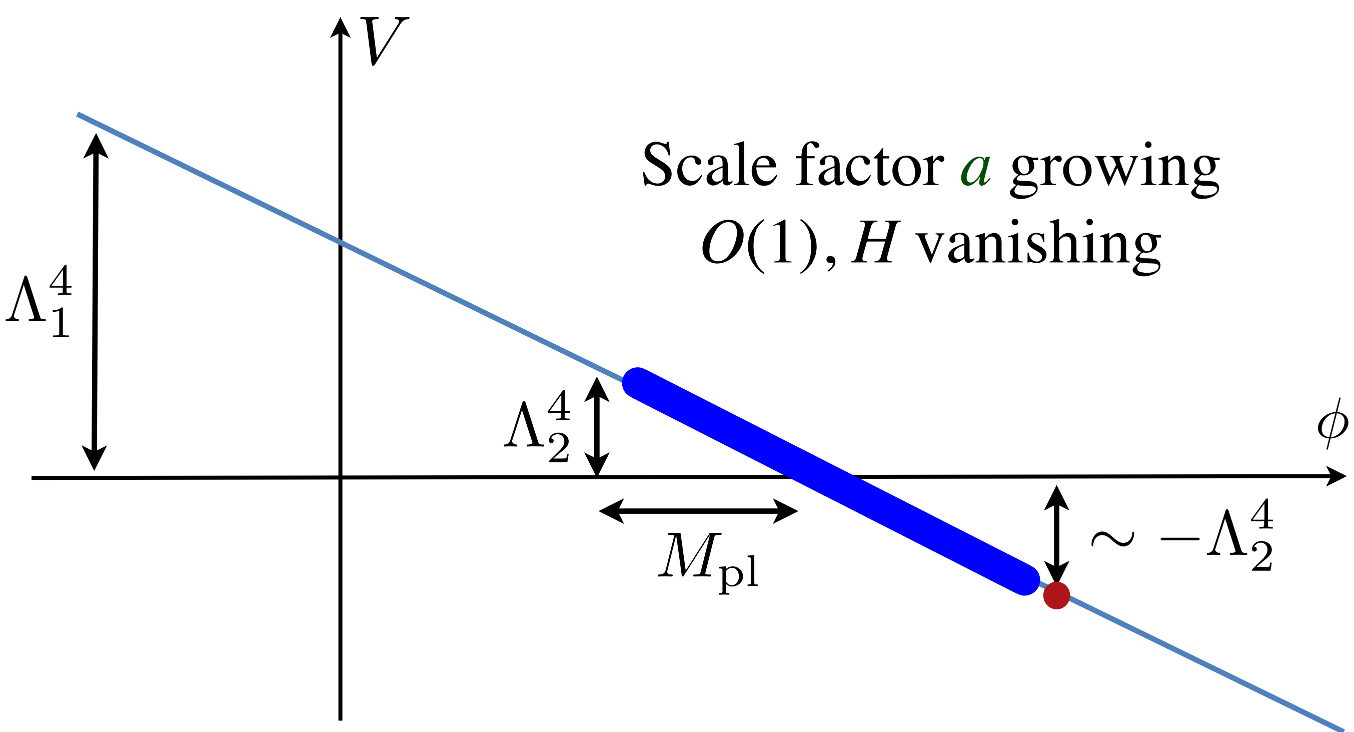
Simplest Model: $\mathcal{L} \supset g^3\phi + \text{arbitrary CC} + \frac{\phi}{f} F'\tilde{F}' + \frac{\phi}{f_G} G'\tilde{G}'$

Avoid eternal inflation at top:

$$H^3 \lesssim V' \;\rightarrow\; g \gtrsim \frac{\Lambda_1^2}{M_{\rm pl}}$$

Fast roll begins: $g^3 M_{\rm pl} \sim \Lambda_2^4$

Together $\rightarrow$ $\boxed{\Lambda_1^3 \lesssim \Lambda_2^2 M_{\rm pl}}$

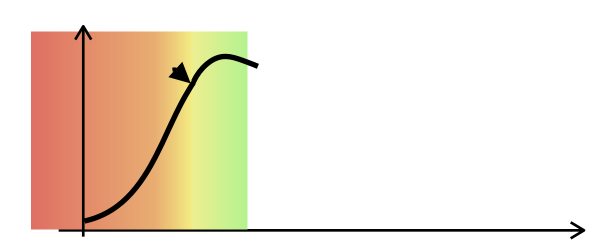


$$H^2 = \frac{1}{3M_{pl}}\left(\frac{1}{2}\dot{\phi}^2 - g^3\phi\right)$$

$$\dot{H} = -\frac{1}{2M_{pl}}\dot{\phi}^2$$

Hubble decreasing monotonically

Vanishes in a finite roll of $\phi \sim M_{\rm pl}$



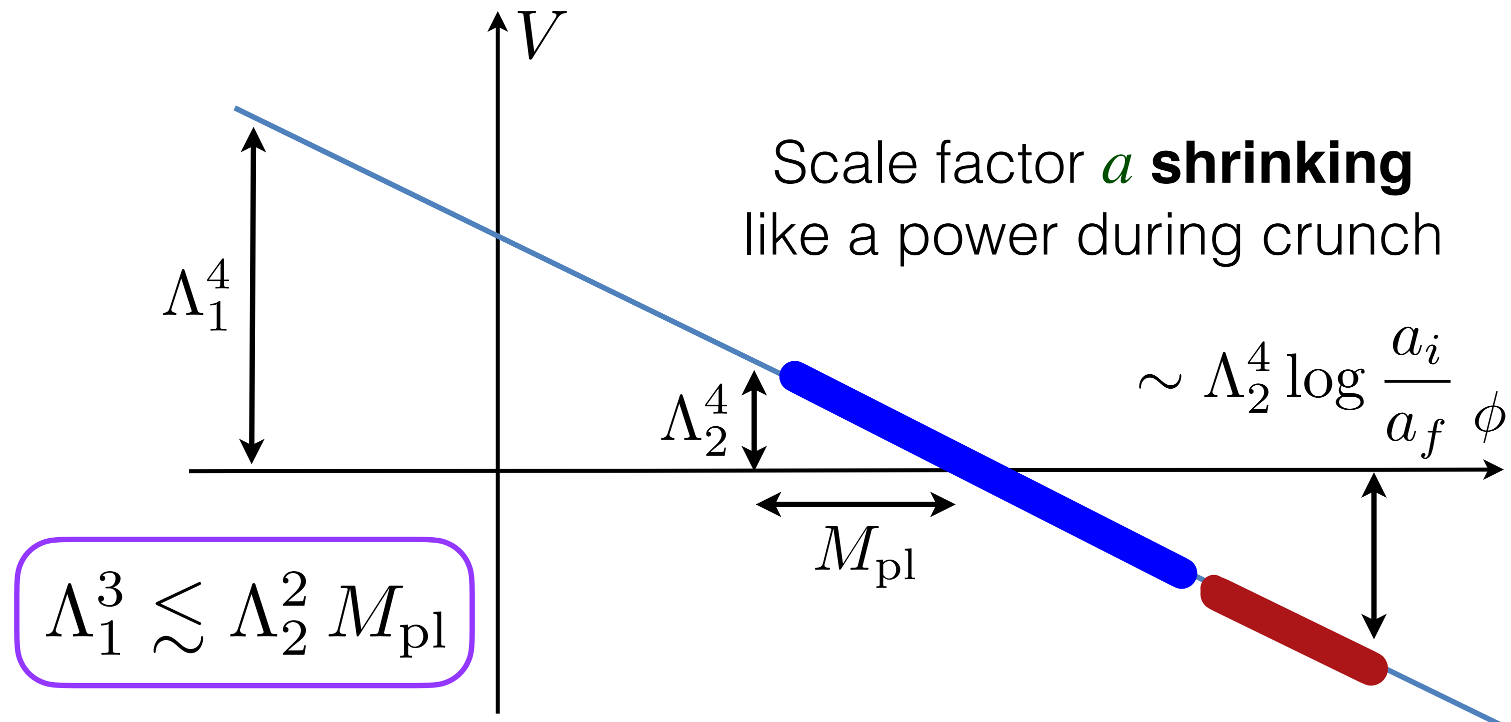
CC Solution: Crunch - K.E. Dom.

Simplest Model: $\mathcal{L} \supset g^3\phi + \text{arbitrary CC} + \frac{\phi}{f} F'\tilde{F}' + \frac{\phi}{f_G} G'\tilde{G}'$

Avoid eternal inflation at top:

$$H^3 \lesssim V' \;\rightarrow\; g \gtrsim \frac{\Lambda_1^2}{M_{\rm pl}}$$

Fast roll begins: $g^3 M_{\rm pl} \sim \Lambda_2^4$

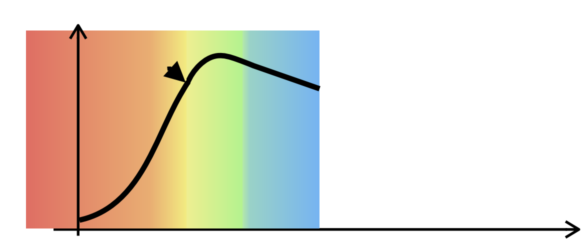


Hubble anti-friction accelerates ϕ rapidly: $\ddot{\phi} + 3H\dot{\phi} - g^3\phi = 0$

During kinetic energy dominance: $\dot{\phi} \propto \frac{1}{a^3}$

$$\Delta\phi \sim \int dt\,\dot{\phi} \sim \int da\,\frac{\dot{\phi}}{\dot{a}} \sim \int \frac{da}{a}\frac{\dot{\phi}}{H} \sim \sqrt{3} M_{\rm pl} \log\frac{a_i}{a_f}$$

Can crunch to extremely small scales
while maintaining a small CC!



CC Solution: Stopping & Reheating

Simplest Model: $\mathcal{L} \supset g^3\phi + \text{arbitrary CC} + \frac{\phi}{f} F'\tilde{F}' + \frac{\phi}{f_G} G'\tilde{G}'$ + coupling btwn groups

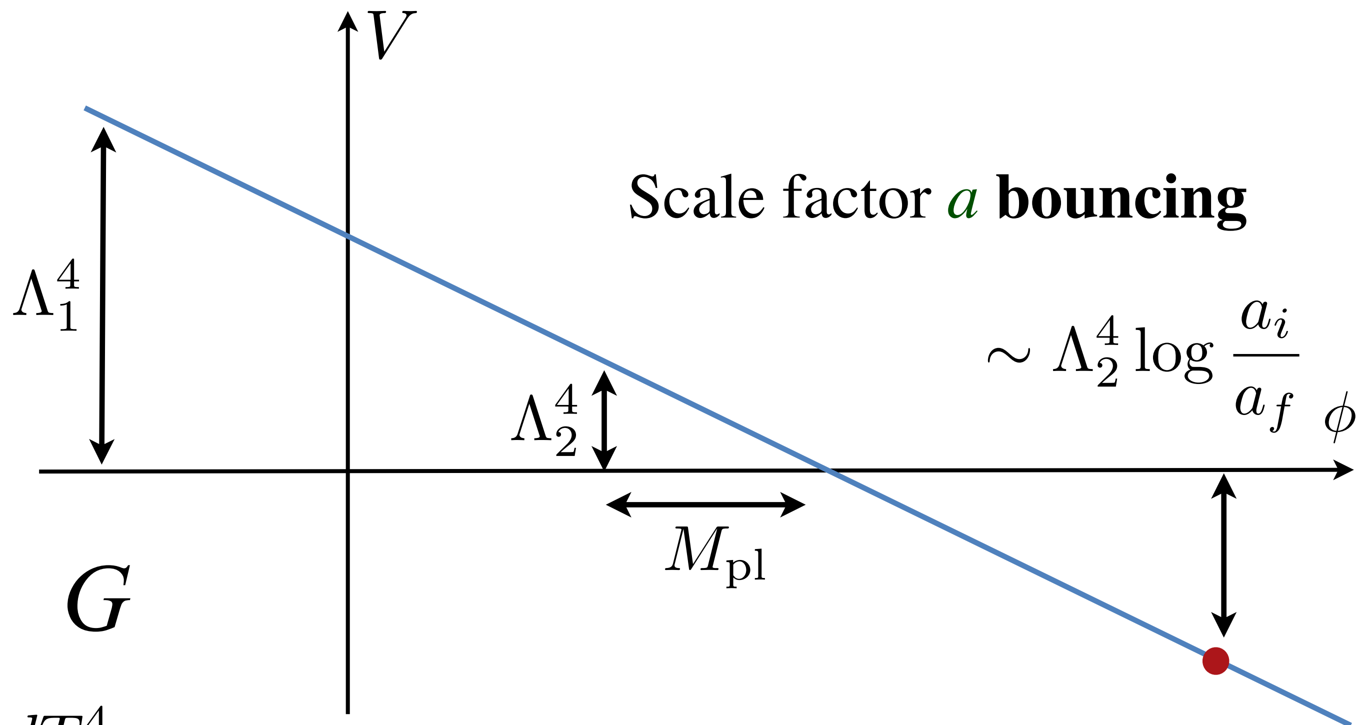
Thermal bath causes extra friction term with coupling to pure Yang-Mills

(e.g. Laine & Vuorinen 2017)

$$\Gamma_{\rm th} \sim \frac{\alpha^3 T^3}{f^2}$$

$$\ddot{\phi} + (3H + \Gamma_{\rm th})\,\dot{\phi} - g^3\,\phi = 0$$

$$(\text{Take } \Gamma_{\rm th} \gg H)$$



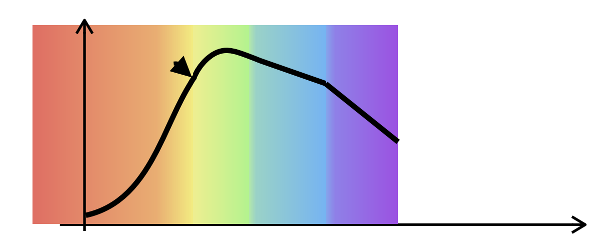
This friction heats thermal bath further $\frac{dT^4}{dt} \sim \Gamma_{\rm th}\,\dot{\phi}^2$ ➜ a runaway

Almost all kinetic energy dumped in a time $\sim \Gamma_{\rm th}^{-1}$ faster than Hubble time ➜ $f_G^2 \lesssim \alpha^3\, T_{\rm reheat}\, M_{\rm pl}$

What starts the runaway? For small H, e.o.m. is $\ddot{A}'_\pm + \left(m_{A'}^2 + k^2 \mp \frac{\dot{\phi}}{f} k\right) A'_\pm = 0$ Anber & Sorbo (2009)

Once $\frac{\dot{\phi}}{f} \gtrsim m_{A'}$, then A'_+ modes become unstable

➜ Coupling between groups causes reheating



all ϕ's kinetic energy rapidly heats that sector once $\dot{\phi}$ large ➜ motion of ϕ stops, CC is fixed

Reheating Details

Simplest Model: $\mathcal{L} \supset g^3\phi + \text{arbitrary CC} + \frac{\phi}{f}F'\tilde{F}' + \bar{\psi}(\not{D} + m)\psi + \frac{m}{2}A'A'$

Last step — reheat the standard model!

Can add mixing with photon (hypercharge):

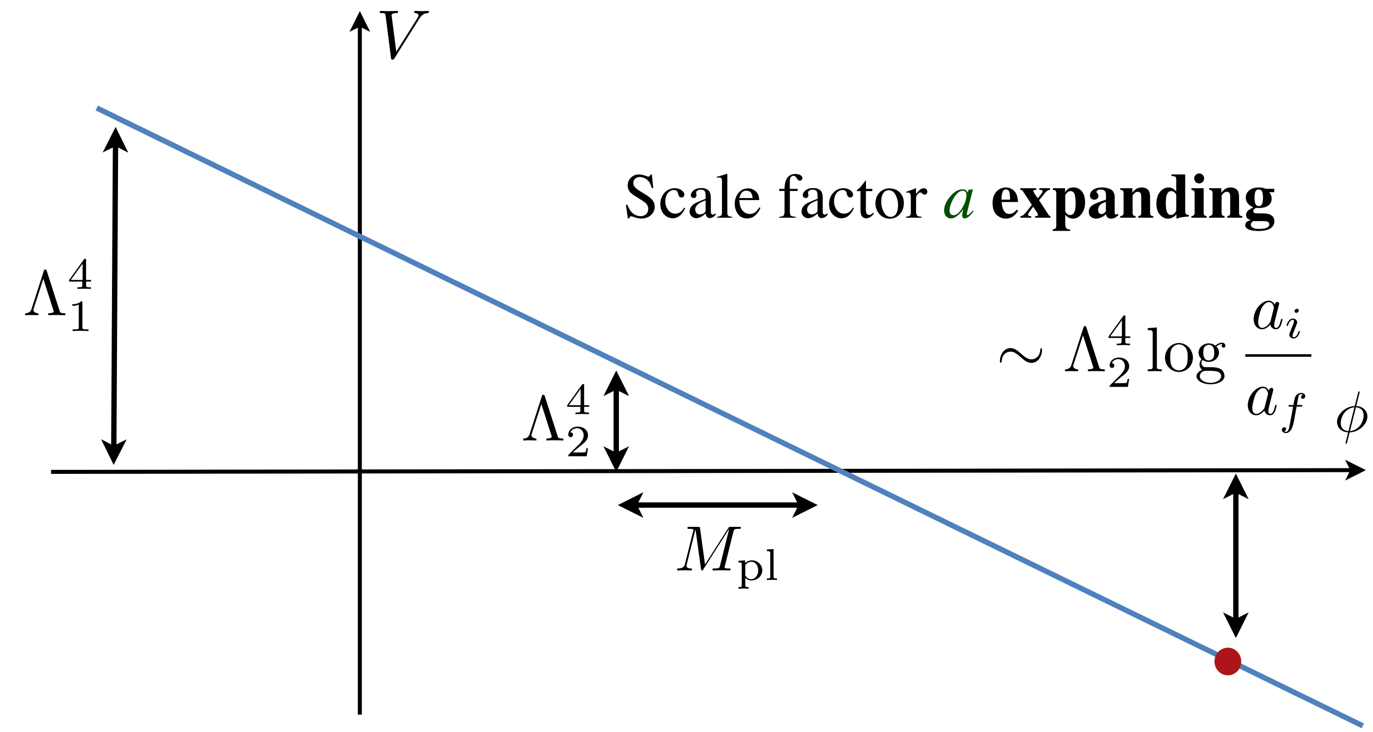
$$\mathcal{L} \supset \epsilon F'_{\mu\nu}F^{\mu\nu}$$

Will cause decays of new sector into SM with rate:

$$\Gamma_{decay} \sim \alpha\epsilon^2 m_{A'}$$

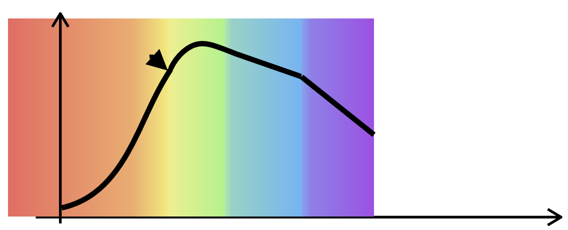
This sets the Hubble time of decay, and temperature:

$$T_d \sim \alpha^{1/2}\epsilon\sqrt{m_{A'}M_p}$$

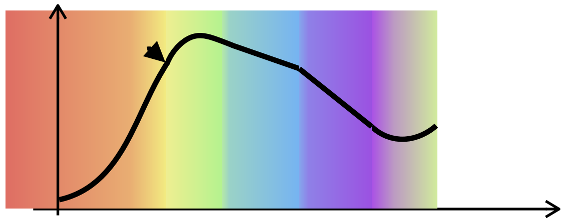


Also produces a direct coupling to photons: $\epsilon^2(\phi/f)F_{\mu\nu}\tilde{F}^{\mu\nu}$

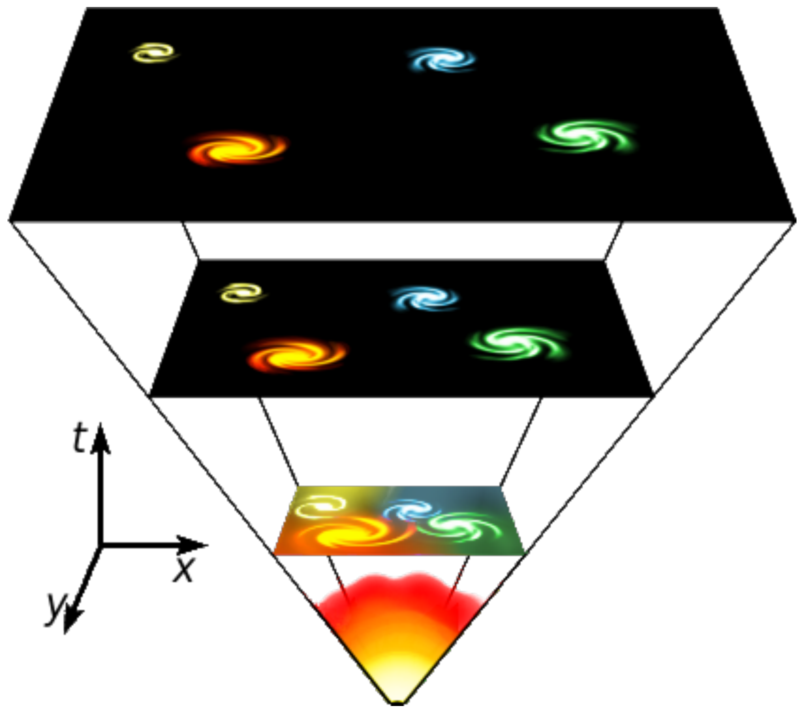
If $f > \epsilon^2 M_p$, then dynamics don't change. However, possible to produce a similar story with photons directly!



The Bounce



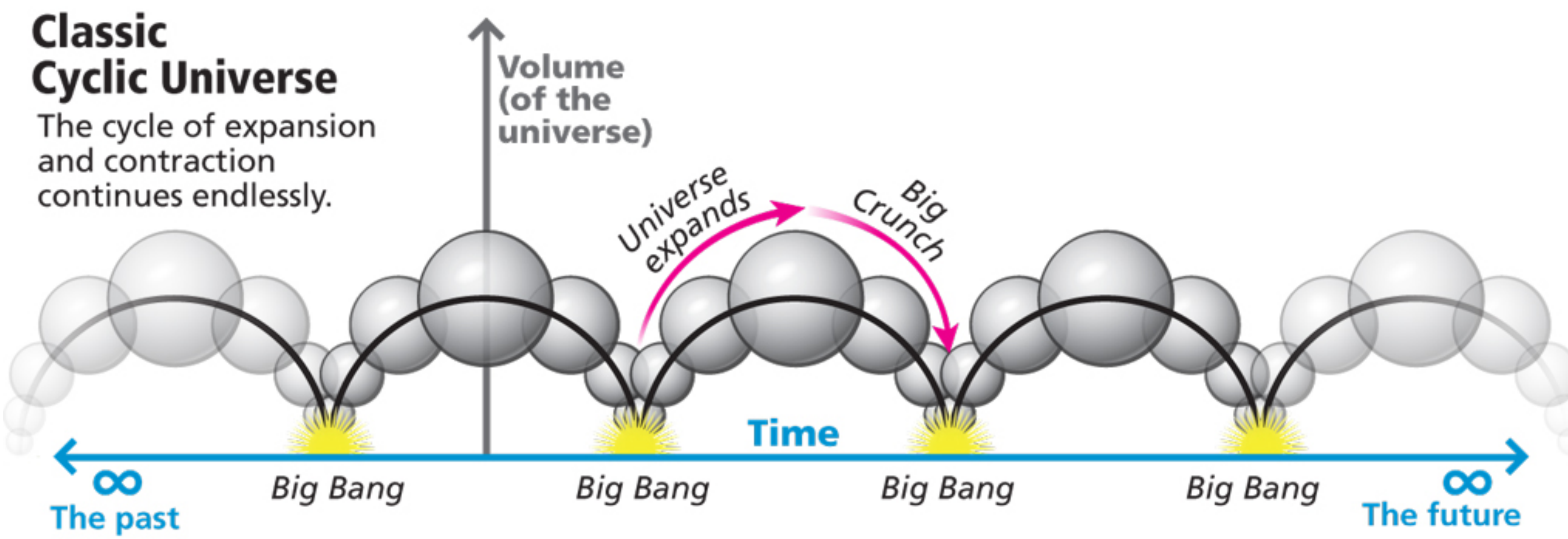
Bouncing Cosmology



Independently Motivated

Singularity not removed by inflation

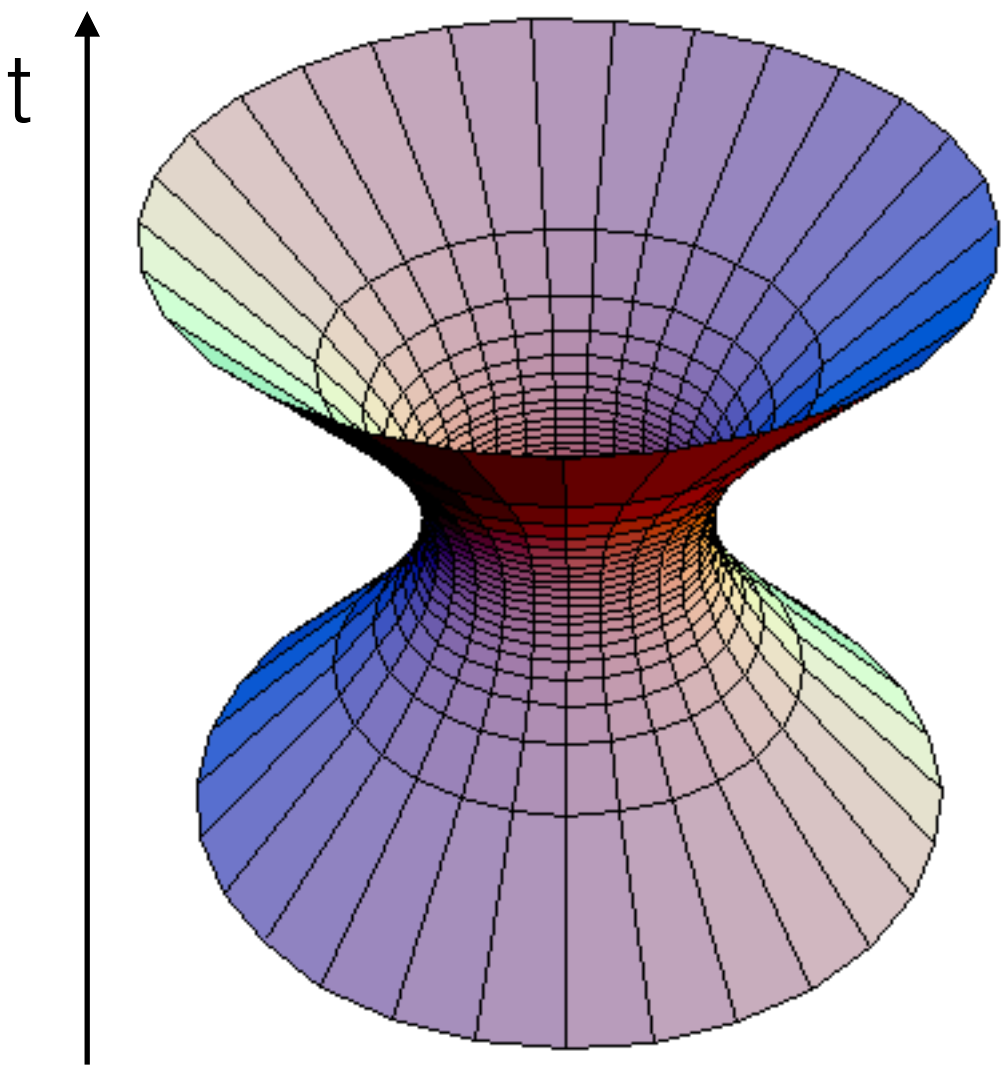
Infinite Past? Why not?



Bouncing Cosmology

Generic Requirement?

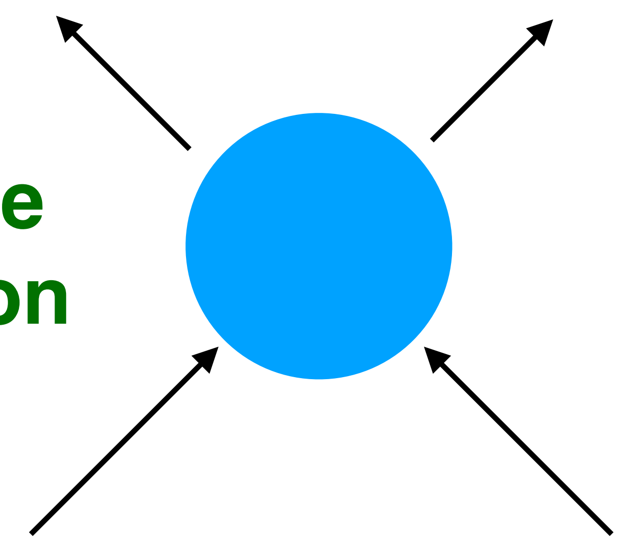
Need converging geodesics to diverge



Collapsing matter, gravity gets stronger

Can matter never escape strong gravity?

Black Hole Evaporation



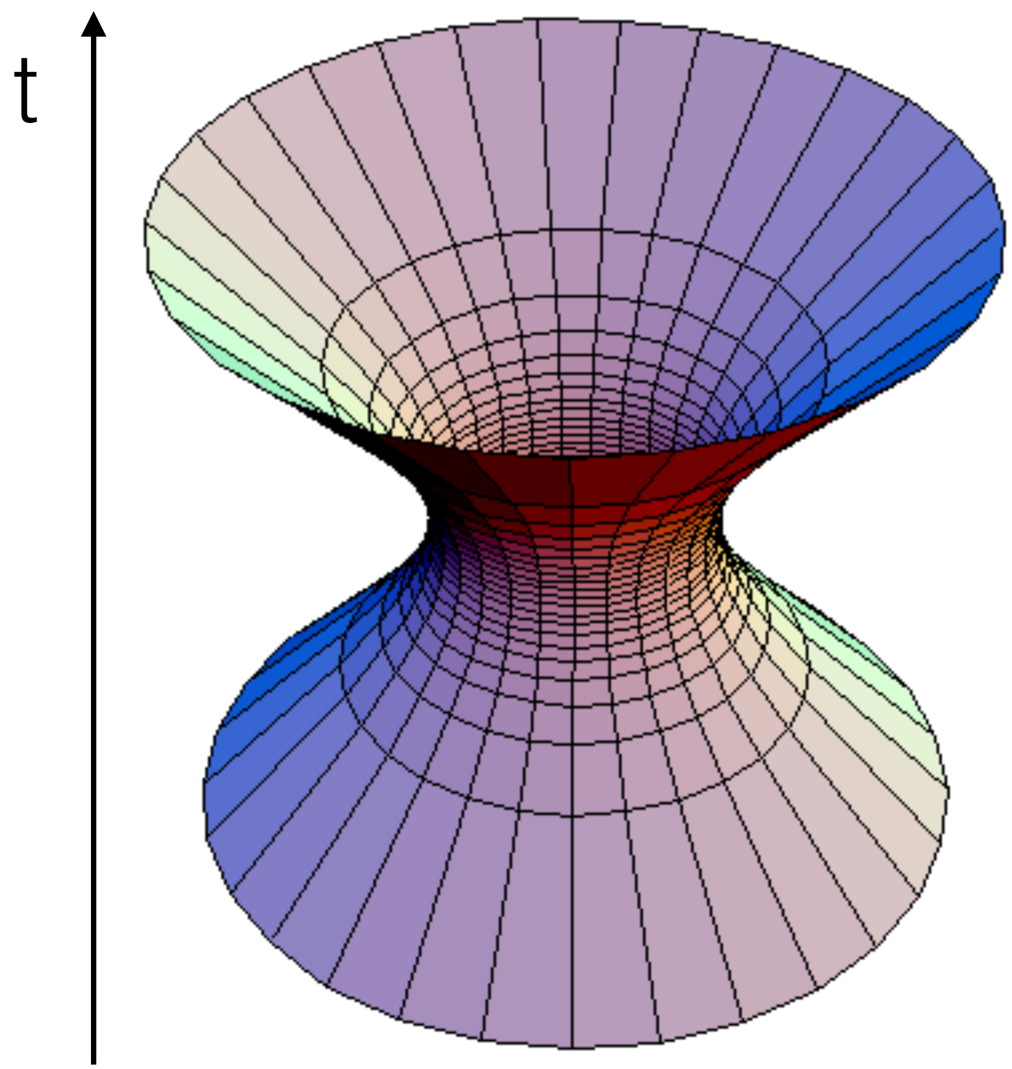
Key Point: Matter could escape gravitational singularities

Singular Bounce likely possible. Non singular bounce?

Bouncing Cosmology

Generic Requirement?

Need converging geodesics to diverge



Raychaudhuri's Equation

$$\frac{d\hat{\theta}}{d\lambda} = -\frac{1}{2}\hat{\theta}^2 - 2\hat{\sigma}^2 + 2\hat{\omega}^2 - T_{\mu\nu}U^\mu U^\nu$$

$$\text{Divergence} \implies \frac{d\hat{\theta}}{d\lambda} > 0$$

$$T_{\mu\nu}U^\mu U^\nu < 0 \text{ or } \hat{\omega} \neq 0$$

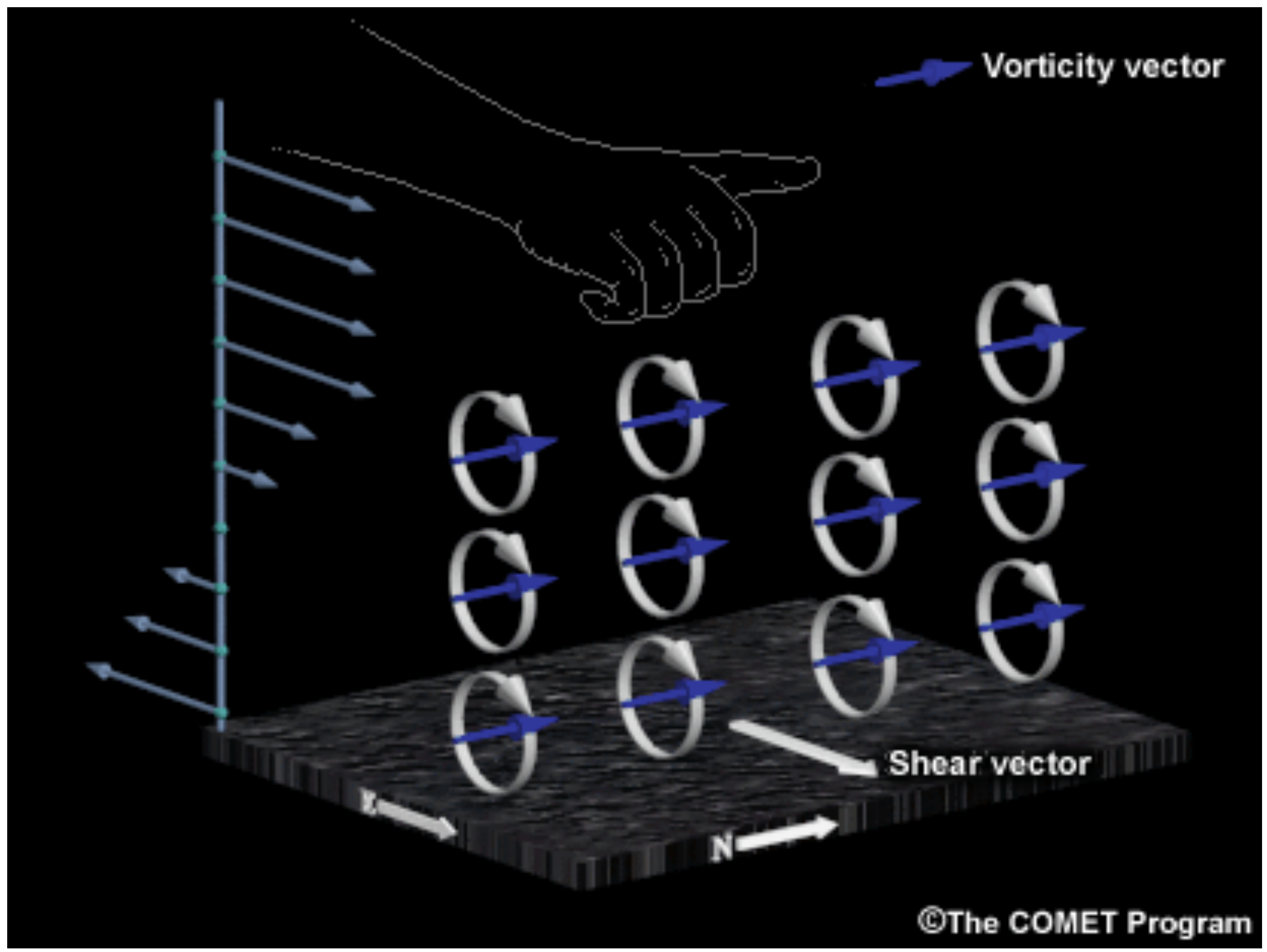
Null Energy Violation ↓ $T_{\mu\nu}U^\mu U^\nu < 0$

Vorticity ↓ $\hat{\omega} \neq 0$

Vorticity

$$\frac{d\hat{\theta}}{d\lambda} = -\frac{1}{2}\hat{\theta}^2 - 2\hat{\sigma}^2 + 2\hat{\omega}^2 - T_{\mu\nu}U^\mu U^\nu$$

Combat attractive gravity with centrifugal motion

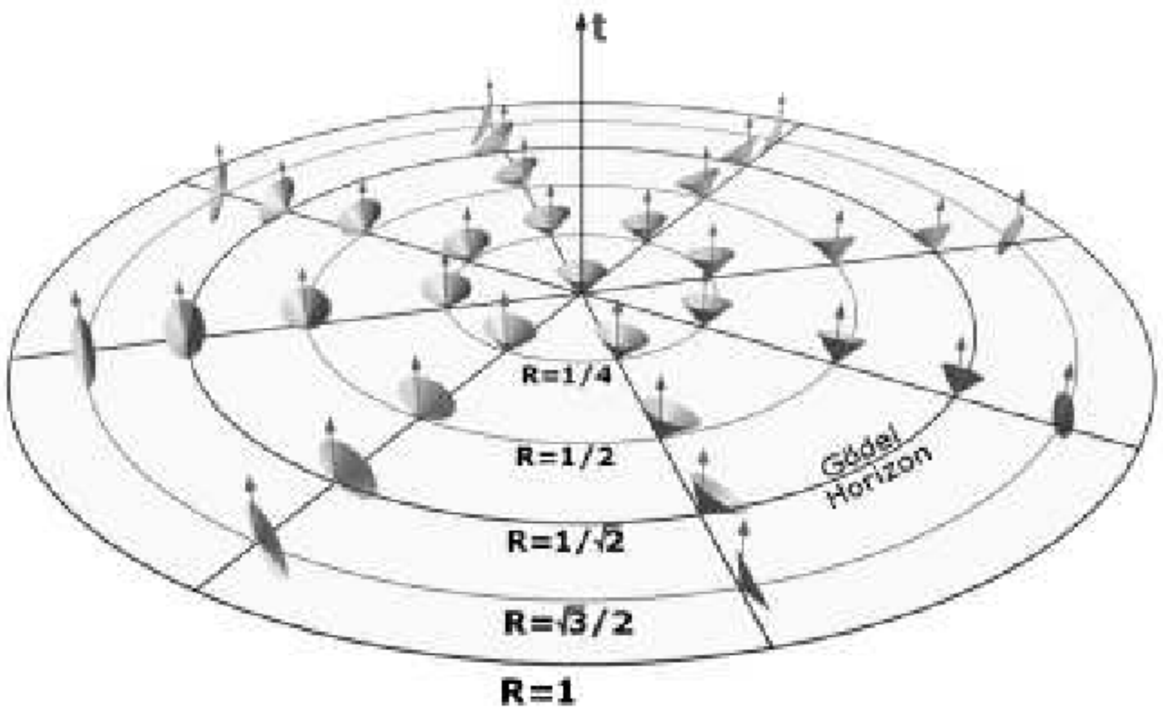


Why not use this term?

To avoid Null Energy violation, need global vorticity

Godel Universe

$$ds^2 = \frac{2}{\omega^2}\left(-dt^2 + dr^2 + dy^2 - \left(\sinh^4 r - \sinh^2 r\right) d\phi^2 - 2\sqrt{2}\sinh^2 r d\phi dt\right)$$



Cosmological Constant + Spinning Dust

Static Universe: Gravity balanced by rotation

Closed time-like curves for $r > 1$

Does not describe region of space-time where we live

The Born Again Universe

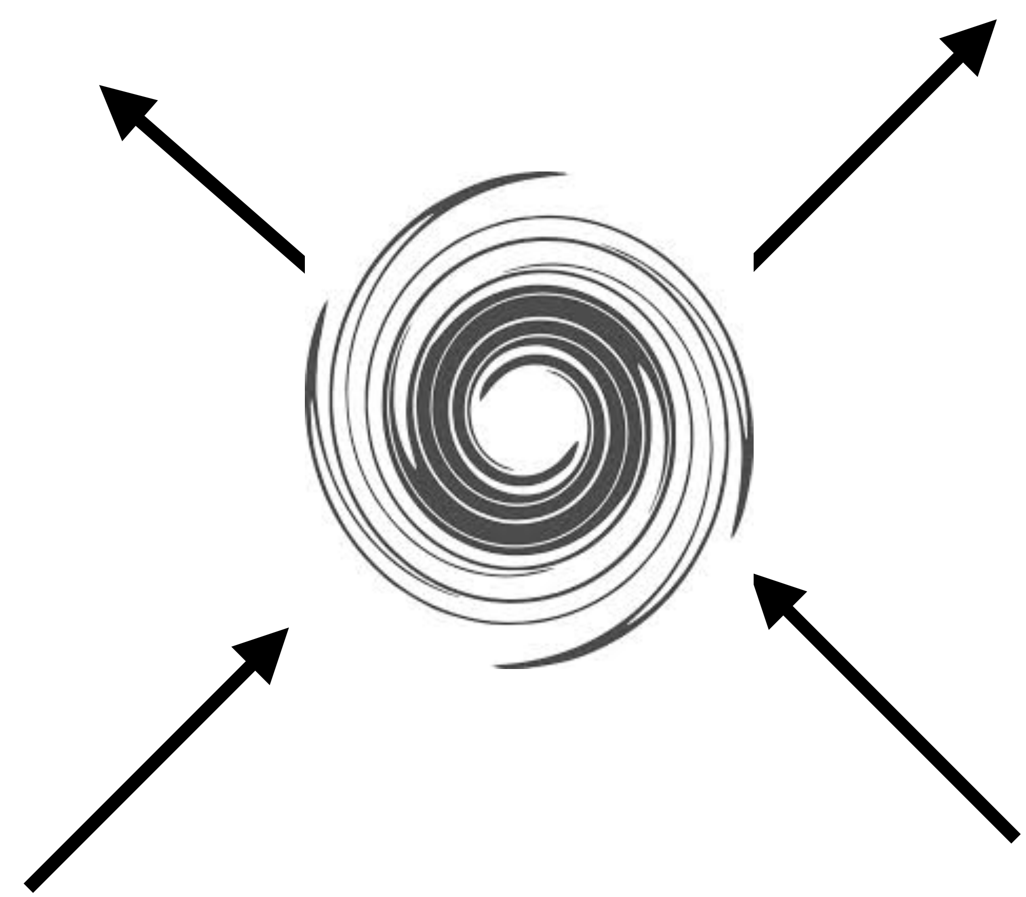
Have vorticity everywhere, without closed time-like curves?

Distant points rotate -> Closed time-like curve

To avoid singularity, just need rotation everywhere

Rotate into compact extra-dimensions!

Space-Time: R^4 x T^3



The Metric

Space-Time: $R^4 \times T^3$

$$ds^2 = -dt^2 + a\left(t\right)^2 d\vec{x}^2 + b^2\left(d\theta^2 + d\phi_1^2 + d\phi_2^2\right) - 2\epsilon b\left(\sin\theta\, dt d\phi_1 + \cos\theta\, dt d\phi_2\right)$$

↓ Standard FRW

↓ **Vorticity**
Geodesics along R^4 forced to move into extra-dimensions

Plug in for a(t), use Einstein's Equations to get stress-tensor

Have Shown: Non-singular Bounce Possible without closed time-like curves

Matter: Positive tension brane gas + stable NEC violating Casimir

Why Relaxing/Bouncing for the Cosmological Constant?

It is easy to raise the starting point with additional friction (few GeV^4) and an additional field (TeV^4). It is also possible to flip the sign of the CC making it positive with a phase transition or other field.

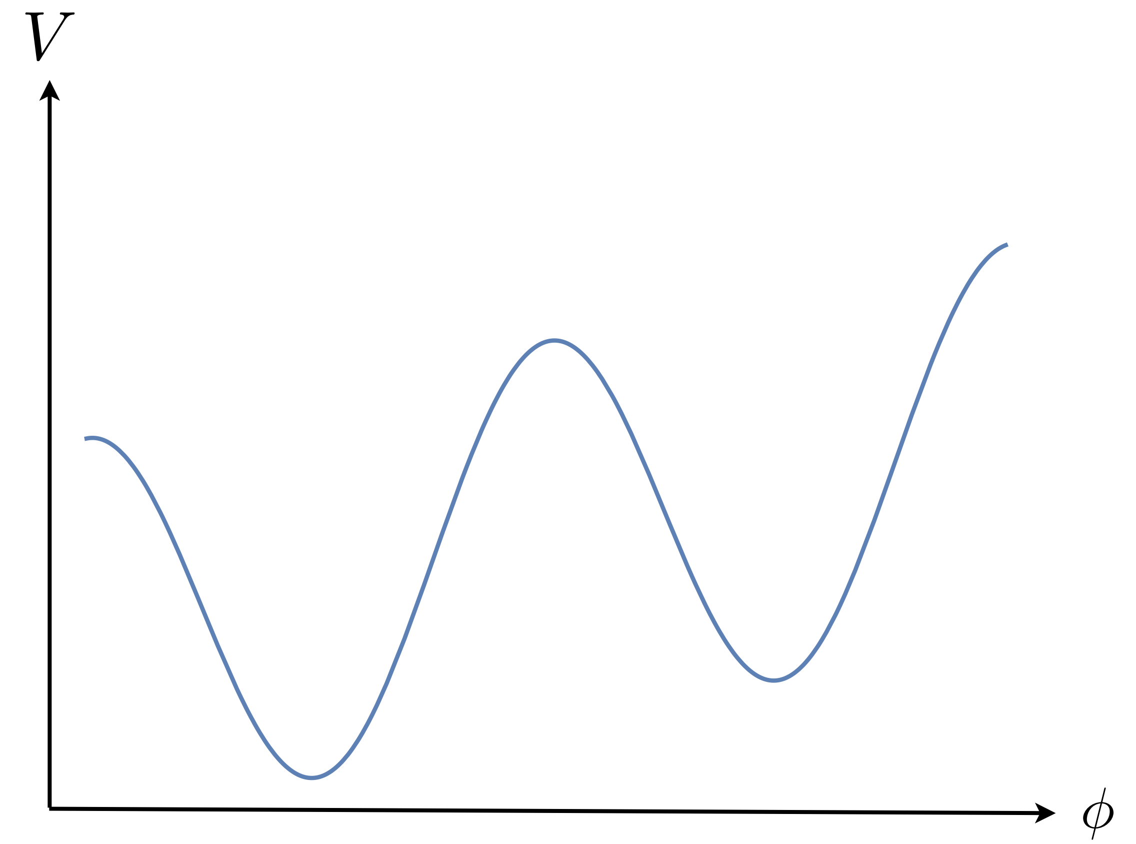
So far, the above model (with a bounce) naturally produces a small negative cosmological constant $-(meV)^4$ and big-bang cosmology from a larger, $(10\ MeV)^4$

It is not possible to have this model without a rolling field existing today…

A Positive CC Model

Add another field (e.g. an axion) with two minima split by ~ meV

this scale is what actually sets today's CC



As universe heats during contraction, temperature gets arbitrarily high

resets field which can then naturally settle later in higher minima

Still preliminary: Ugly scalar field theories work, possibly confining YM

Models of Dark Energy

I. Rolling ϕ

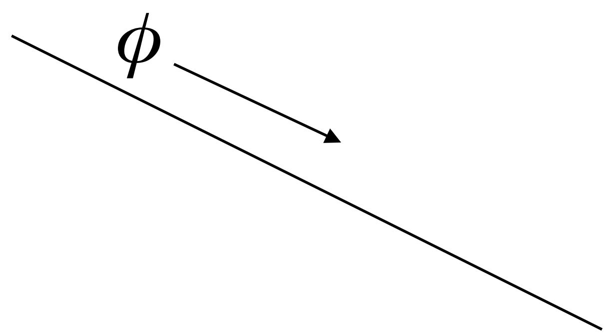
II. Rolling ϕ coupled to SM

III. Dark Radiation

Rolling ϕ

CC solution suggests a field still rolling today

Simple rolling scalar: Quintessence



$$w = \frac{\frac{\dot{\phi}^2}{2} - V}{\frac{\dot{\phi}^2}{2} + V}$$

Lagrangian for this scalar field?

$$m \lessapprox H = 10^{-43}\ \mathrm{GeV}$$

Ultra-light field. Demand technical naturalness => axion-like, derivative interactions

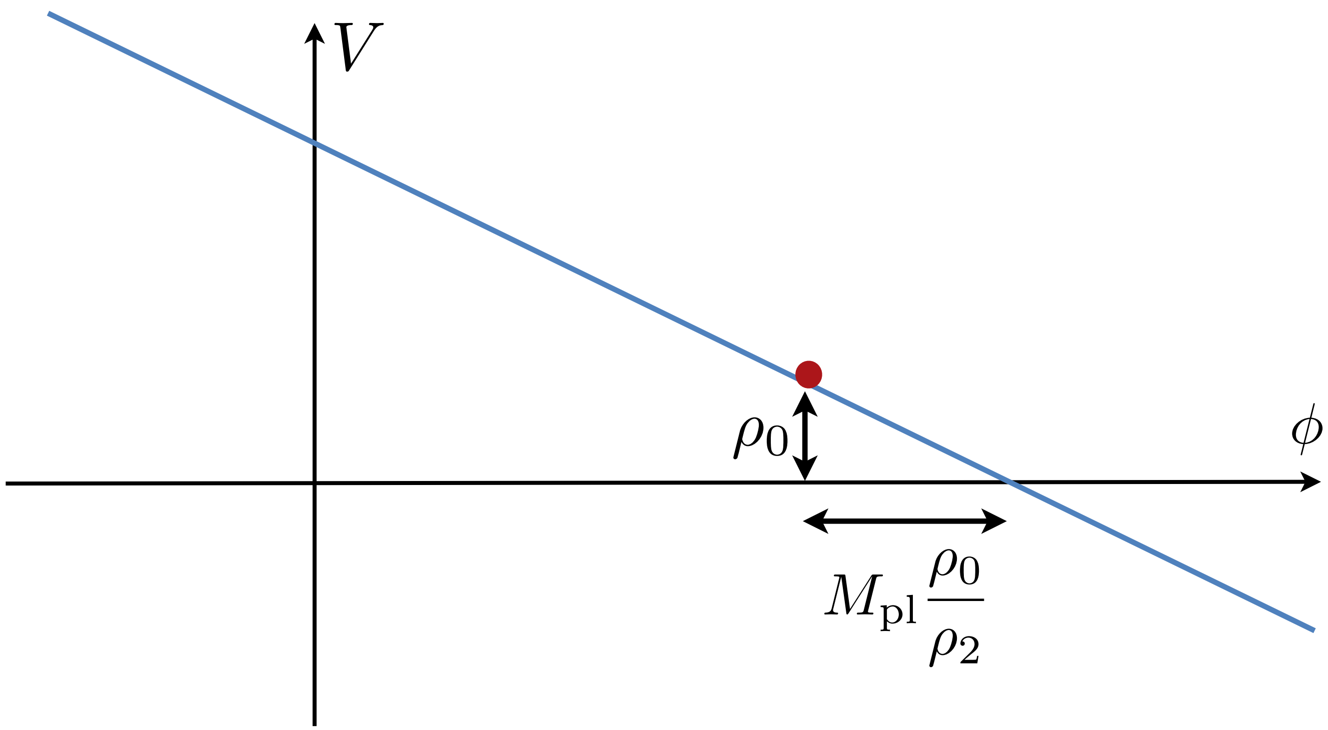
$$\mathcal{L} \supset C\phi + \frac{\partial_\mu \phi}{f_a}\bar{\psi}\gamma^\mu\gamma_5\psi + \frac{\phi}{f_a}F\tilde{F}$$

Kinetic Energy of Dark Energy < meV^2

Direct Detection

Signatures: Dark Energy E.O.S.

The equation of state, w, will depend on how much was added to make CC positive



ρ_0 = measured CC today

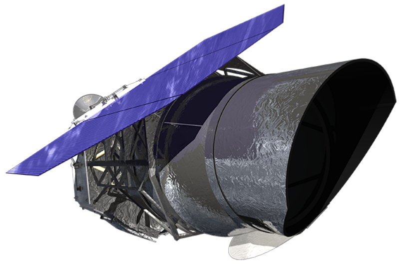
ρ_2 = fast-roll energy scale

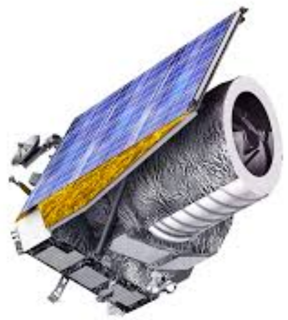
$$\delta w \sim \frac{\dot{\phi}^2}{\rho_0} \sim \left(\frac{\rho_2}{\rho_0}\right)^2$$

Currently constrained at the 5-10% level

Many upcoming experiments will measure w better, e.g. WFIRST, Euclid, gravitational waves…

Could make a discovery, hard to rule out parameter space

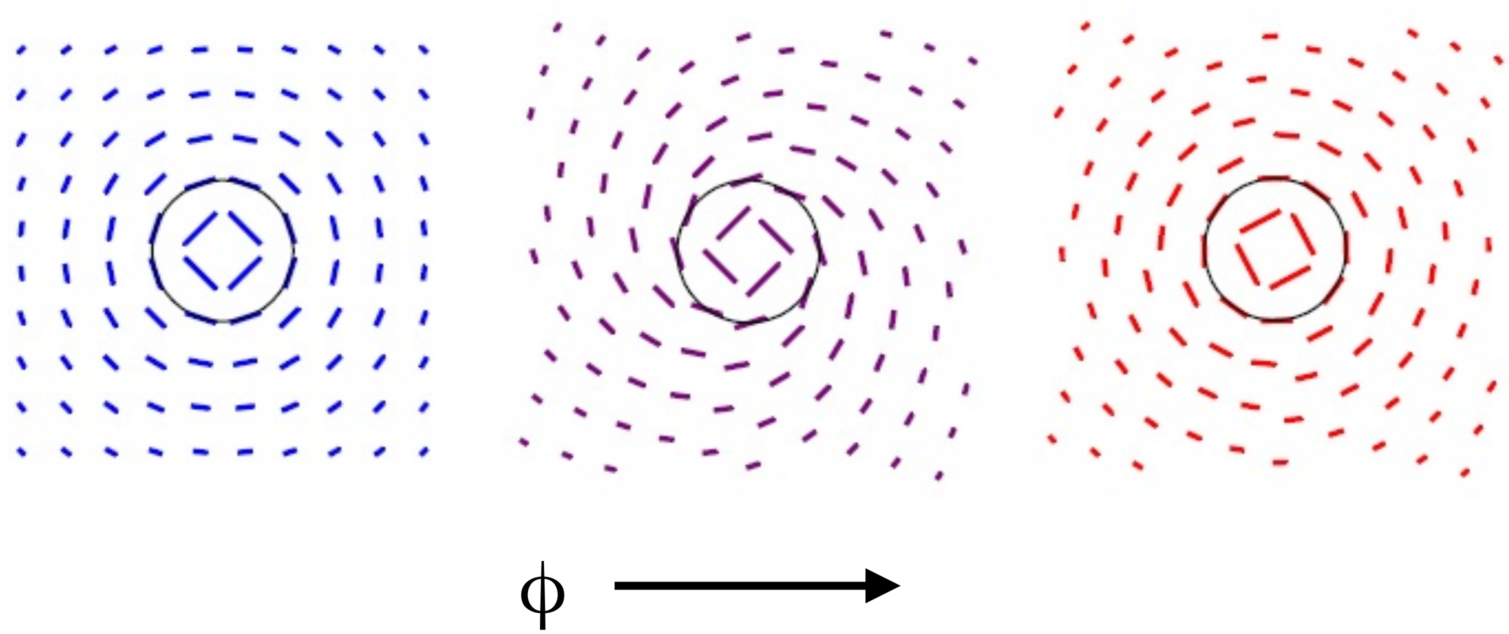




Rolling ϕ Coupled to CMB

$$\frac{\phi}{f_\gamma} F\tilde{F}$$

$$\dot{\phi} \implies \text{Rotation of polarization of light}$$



The polarization of the CMB rotates as ϕ rolls (Homogeneous scalar)

E-mode => B-mode

$$\frac{\dot{\phi}}{f_\gamma}\frac{1}{H} = \frac{\dot{\phi}}{\text{meV}^2}\frac{M_{pl}}{f_\gamma} \lesssim 1$$

Current CMB Measurements already very constraining!

Future CMB polarization measurements (*e.g.*, CMB-S4, etc): $\delta w \left(\frac{M_{pl}}{f}\right)^2 < 2 \times 10^{-9}$!

Pogosian, Shimon, Mewes, Keating (2019)

Rolling ϕ Coupled to Fermions: Spin Precession

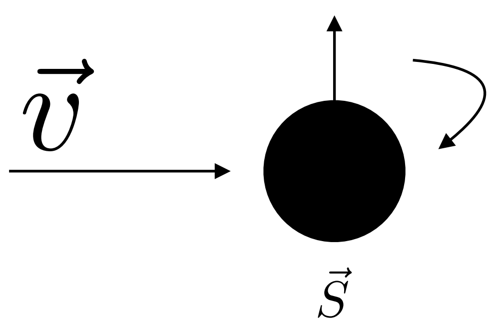
$$\frac{\partial_\mu \phi}{f_\psi} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

$$H = \frac{\vec{\nabla}\phi}{f} \cdot \vec{\sigma}_\psi$$

Relative Motion between the dark energy and spin

Think of it as a new dark magnetic field

Like magnetic field, spin precesses about the direction of motion



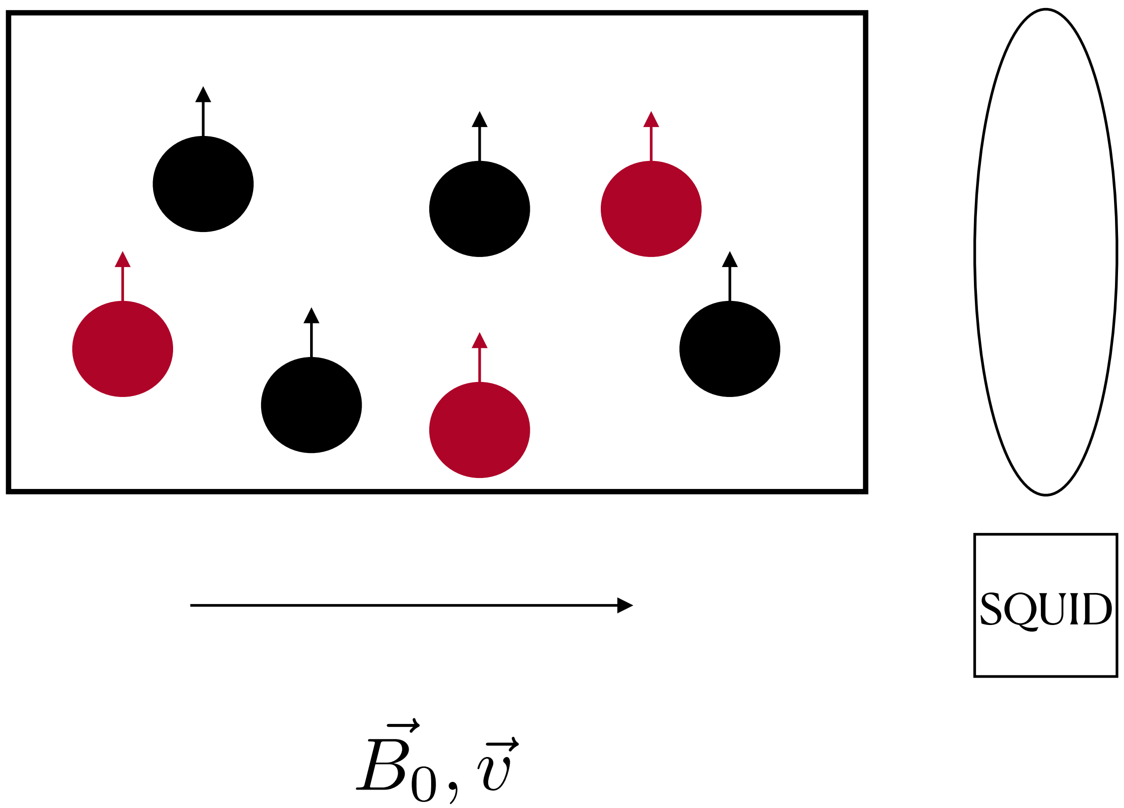
Measure Spin Precession - similar to axion dark matter searches (CASPER)

Challenges: Signal is DC - need to combat low frequency noise, Dark energy is less abundant in galaxy than dark matter

Advantage: Signal is coherent forever

Spin Precession

Many experiments look for Lorentz Violation



Dual Species Magnetometry
(Xe/He, Xe/K, Xe/Rb)

Measure Differential Precession Rate

In general, ratio of magnetic moments different from ratio of dark energy couplings

Anomalous relative precession indicative of dark energy

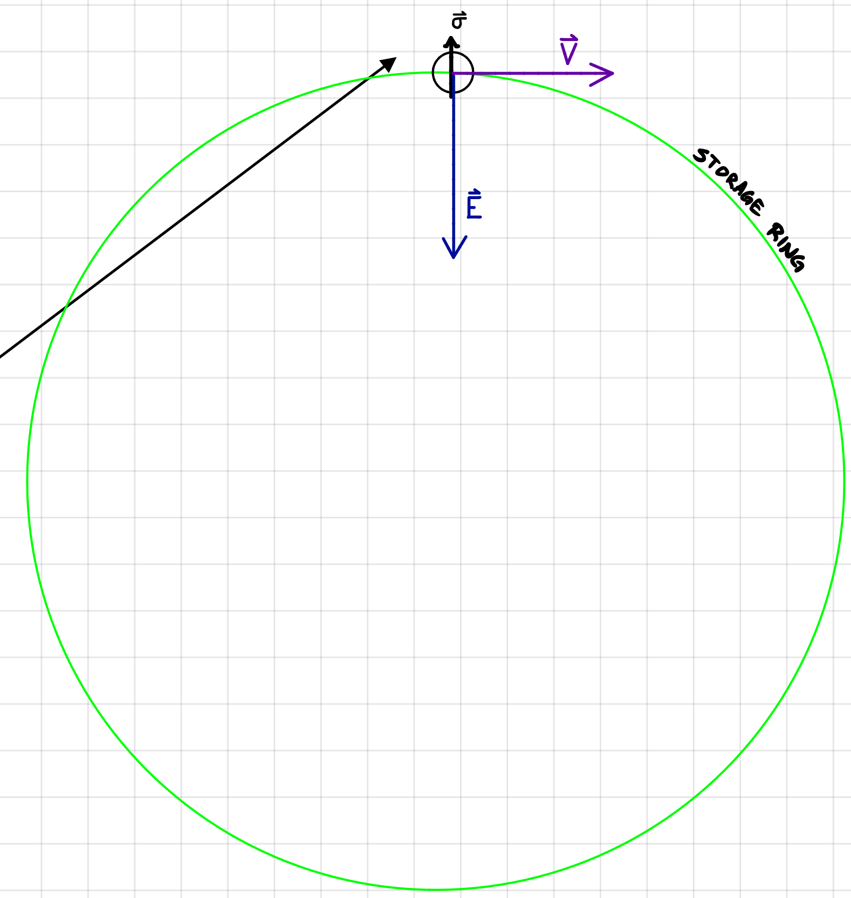
Signatures: Spin Precession

ϕ has non-gravitational couplings — could couple to SM fermions $\frac{\partial_\mu \phi}{f} \bar{\psi}\gamma^\mu \gamma^5 \psi$

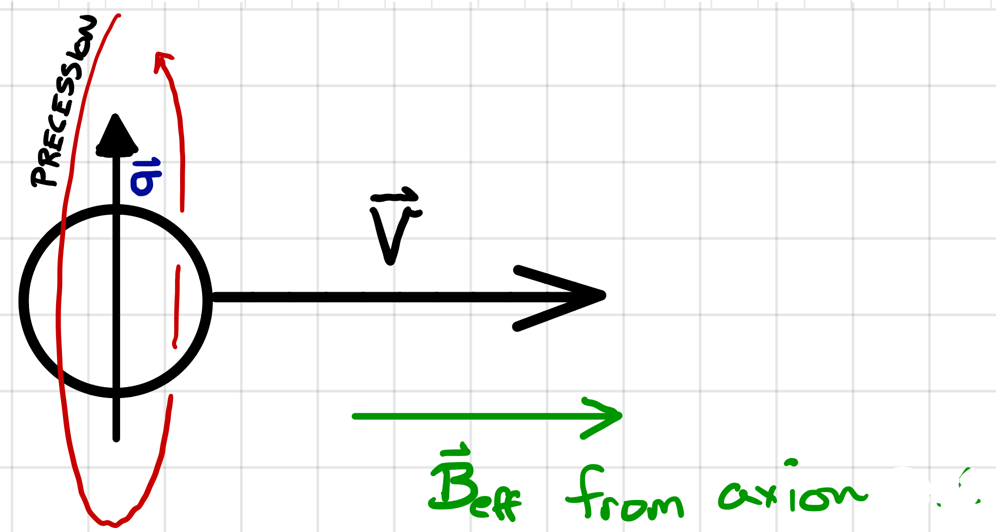
Spatial gradient of axion field ➜ spin precession in 'axion wind' $H = \frac{\vec{\nabla}\phi}{f} \cdot \vec{\sigma}_\psi$

Cosmological axion field **dominantly homogeneous**, but can use a **highly boosted** experiment!

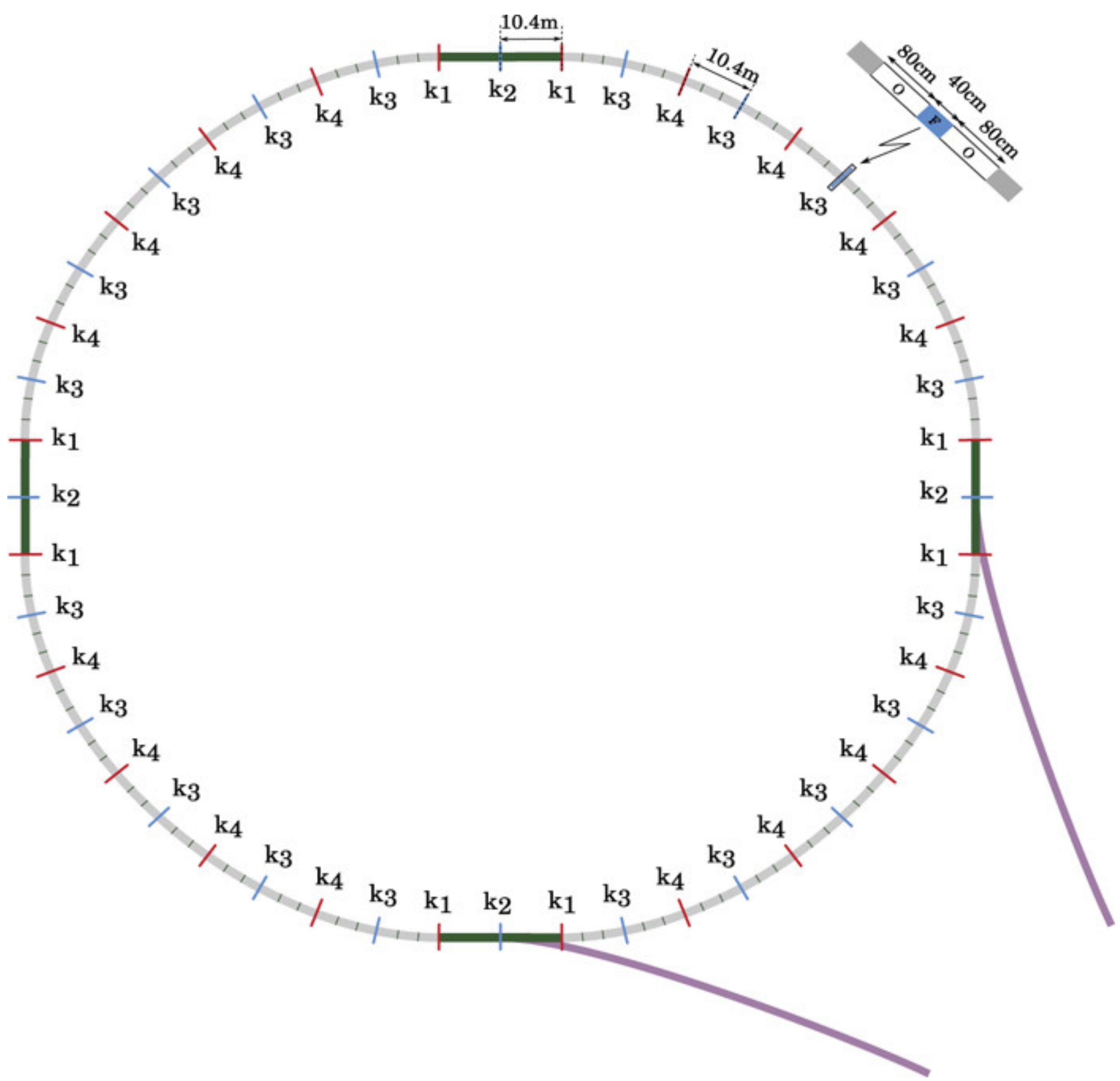
Spin fixed to be radial at magic momentum without signal.



$\vec{\nabla}\phi$ acts as an effective magnetic field acting on the spin causing precession out of the plane



Spin Precession



Storage Ring EDM Experiment:
Look for anomalous precession induced by EDM of proton

Systematics well understood
Development underway
(Brookhaven, Fermilab, IBS Korea)

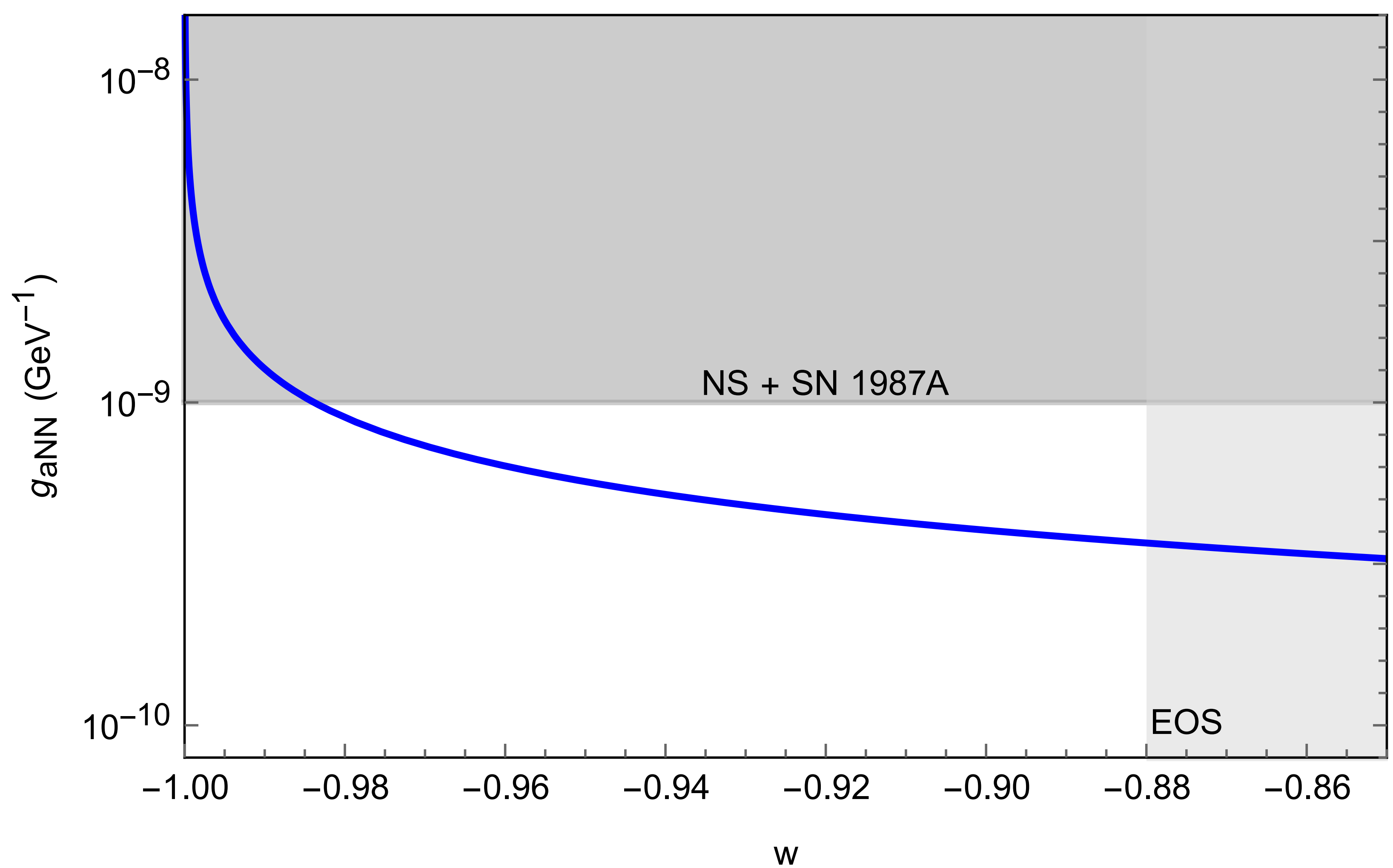
Same setup can be used - but orient spin radially, so that it precesses out of the plane

Relativistic Beam Velocity increases signal

Use counter-propagating beams to combat systematics

P Graham, S Hacıömeroğlu, Z Omarov, S Rajendran, Y Semertzidis - 2005.11867

Projected Sensitivity



Stores protons for ~1000 s

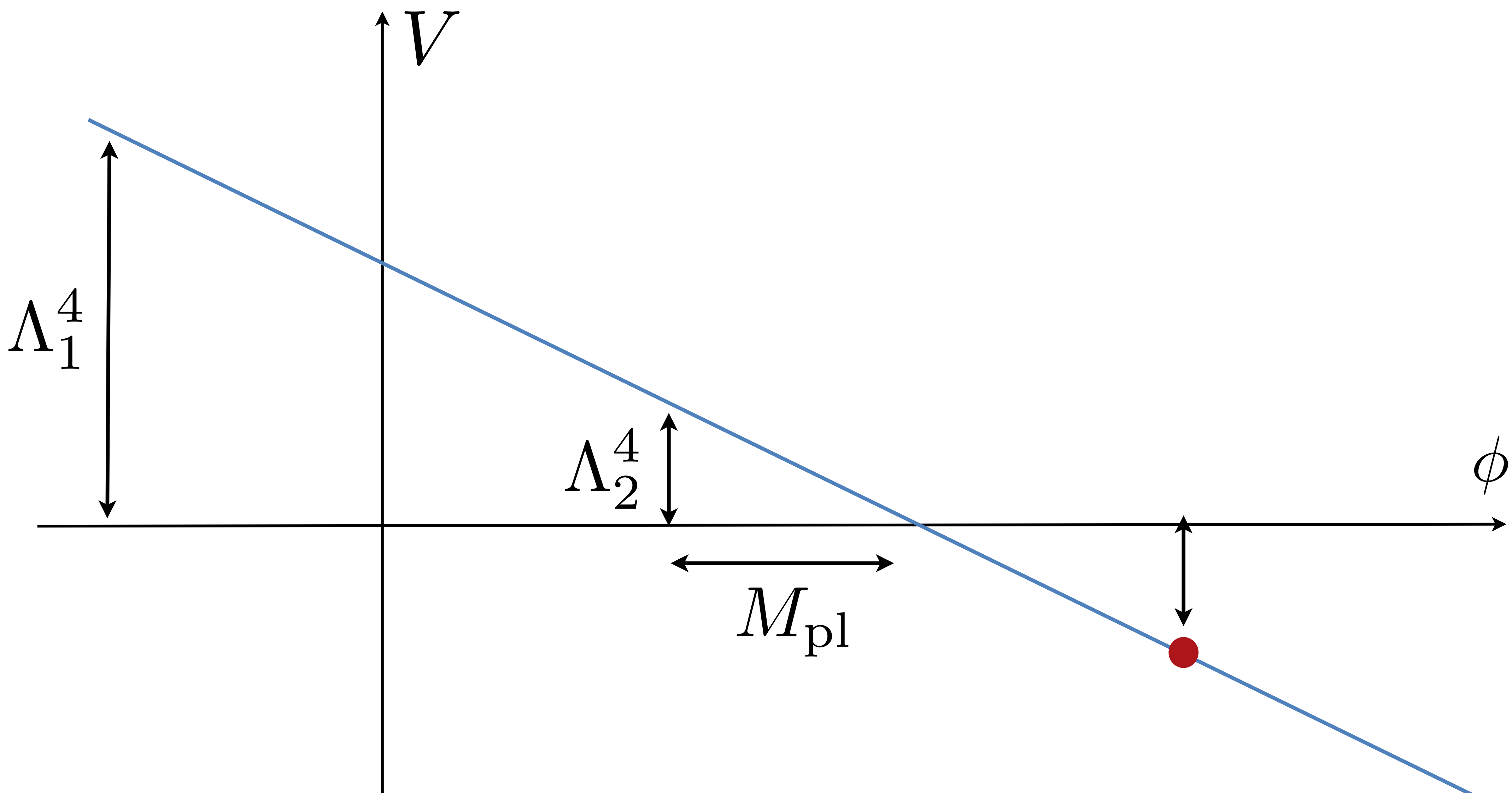
Measure spin precession to 10^{-6} rad

Lorentz Violation experiments also have comparable sensitivity

Dark Radiation

$$\ddot{\phi} + 3H\dot{\phi} + \Upsilon\dot{\phi} = g^3$$

New source of friction



Dark Radiation

Coupling rolling ϕ to pure YM

$$-\mathscr{L} = \frac{1}{2g^2}\,\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{\phi}{f}\frac{\mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}}{16\pi^2} - g^3\phi$$

the pure derivative coupling: $\frac{1}{16\pi^2}\mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu} = \partial_\mu K^\mu$

is natural and related to CS number:

$$N_{\mathrm{CS}}(t) \equiv \int_0^t dt \int d^3x\, \frac{1}{16\pi^2}\mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu} = \int d^3x\, K^0$$

So $\dot{\phi}/f$ is a source for N_{CS} in the action — in Euclidean space it is a chemical potential, $\mu(t)$.

Dark Radiation

Now, the scalar EOM: $\ddot{\phi} = g^3 + \frac{\mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}}{16\pi^2 f}$

We want the last (source) term in a thermal background.

Without the scalar field, there are sphaleron transitions which fluctuate:

$$\langle N_{\mathrm{CS}}^2 \rangle \simeq V t \Gamma_{\mathrm{sph}}$$

The sphaleron rate, from dim anal, should go as T^4
More accurately:

$$\Gamma_{\mathrm{sph}} \sim N_c^5 \alpha^5 T^4$$

Dark Radiation

The fluctuation-dissipation theorem relates fluctuations of $N_{\rm CS}$ to response to the $\mu(t)$ source.

For a system with a driving source $\hat{H} \to \hat{H}(t) = \hat{H} - \mu(t)\hat{N}(t)$

If the system is in a thermal bath, and the source turns on at some time:

$$\langle N(t)\rangle_{\rm non-eq} = {\rm Tr}\left[\rho(t)N(t)\right] \simeq i\int_{-\infty}^{t} \mu(t'){\rm Tr}\left[\left[N(t'),\rho(-\infty)\right]N(t)\right] = i\int_{-\infty}^{t} \mu(t')\langle\left[N(t),N(t')\right]\rangle_{\rm eq}$$

A time-derivative of the left side give the expectation value we want and relates it to the fluctuations in N:

$$\left\langle \frac{{\rm Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}}{16\pi^2}\right\rangle = \frac{\Gamma_{\rm sph}}{2T}\left(\frac{\dot{\phi}}{f}\right)$$

Dark Radiation

Thus a thermal bath of YM produces a new source of friction for a rolling scalar field:

$$\ddot{\varphi} + 3H\dot{\varphi} + \Upsilon\dot{\varphi} = g^3 \qquad \text{with} \qquad \Upsilon \sim (N_c\alpha)^5 \frac{T^3}{f^2}$$

If $\Upsilon \gg H$, the friction extracts energy from the rolling field and dumps it into the thermal bath:

$$\dot{\rho}_{DR} = -4H\rho_{DR} + \Upsilon\dot{\varphi}^2$$

Assuming roughly steady state behavior ($\dot{T} = 0$, $\ddot{\phi} = 0$):

$$\dot{\phi} \simeq \frac{g^3}{\Upsilon} \qquad \text{and} \qquad T \sim \left(\frac{g^6 f^2}{H g_* N_c^5 \alpha^5}\right)^{1/7}$$

Dark Radiation

$$\dot{\phi} \simeq \frac{g^3}{\Upsilon} \qquad T \sim \left(\frac{g^6 f^2}{H g_* N_c^5 \alpha^5} \right)^{1/7} \quad \text{and} \quad \dot{\phi}^2 \sim \frac{H}{\Upsilon} \rho_{DR}$$

Thus, if $\Upsilon \gg H$, the dark radiation can be a significant component of dark energy while the kinetic energy is negligible.

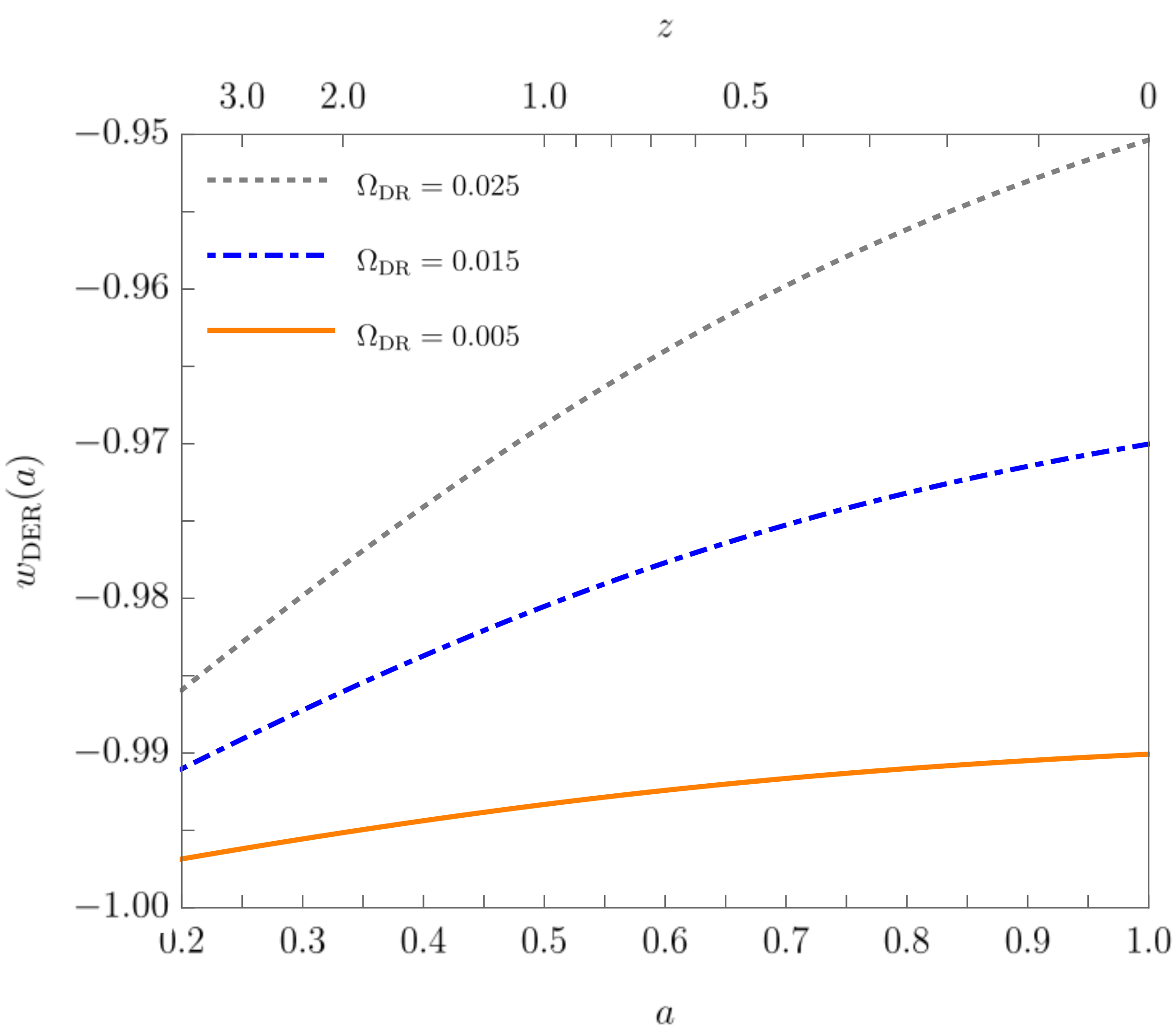
Coupling needs to be strong enough (low enough scale) — for example, if $T \sim \mathrm{meV}$ today, then $\Upsilon \gg H$ means $f \ll T\sqrt{T/H_0} \sim \mathrm{TeV}$ (hidden sector).

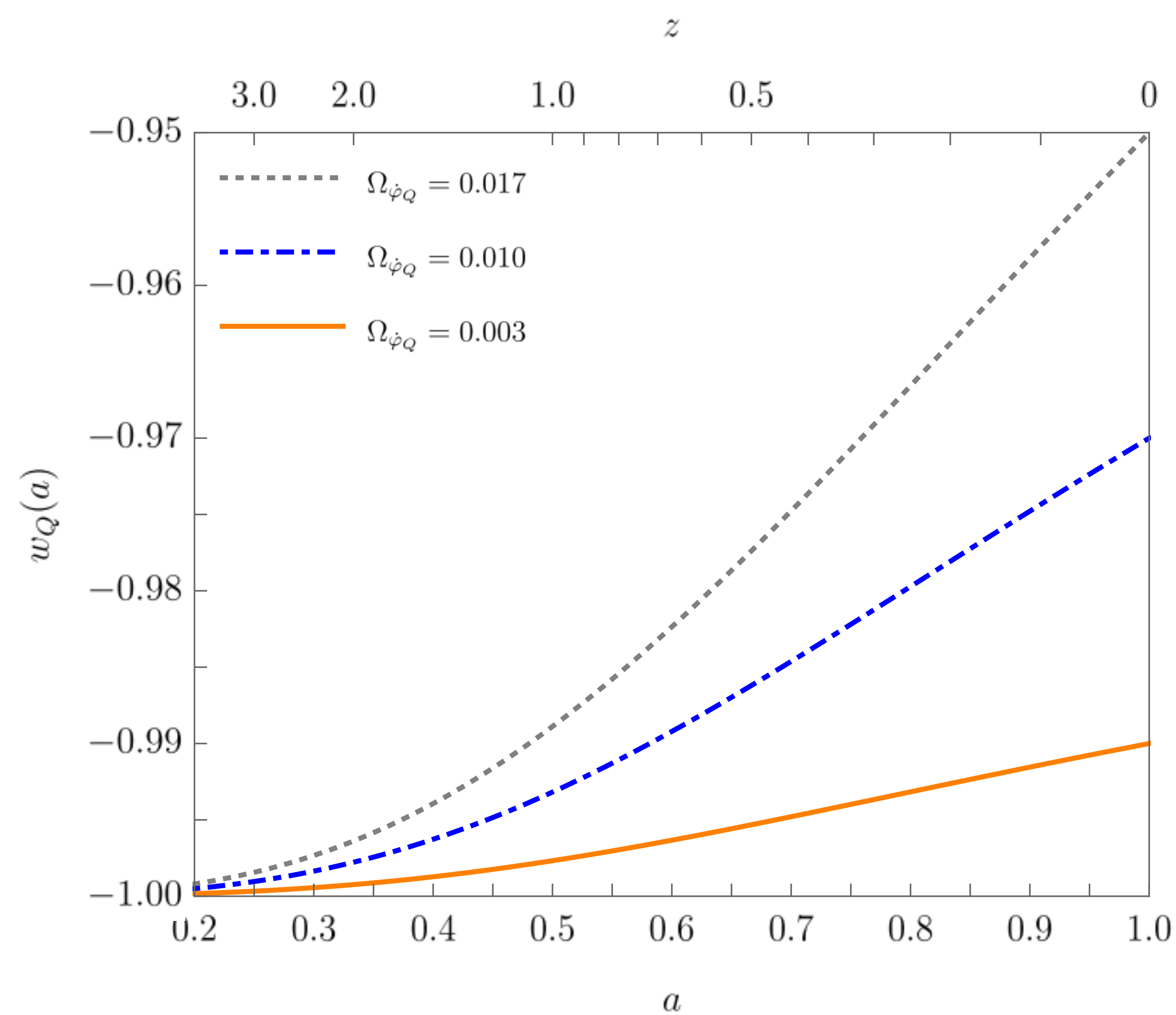
This solution has a large basin of attraction - even for zero T at early times, a finite T will be generated via scattering and tachyonic instability

Cosmological Effects

Dark radiation does not affect CMB — large today, but meV vs. eV at recombination.

Significantly different from quintessence





Direct Detection

$$\frac{\bar{\psi}\psi G^2}{\Lambda^3}$$

Direct coupling to the Standard Model is dimension 7. Hard to probe

But dark sector doesn't have to be pure YM:

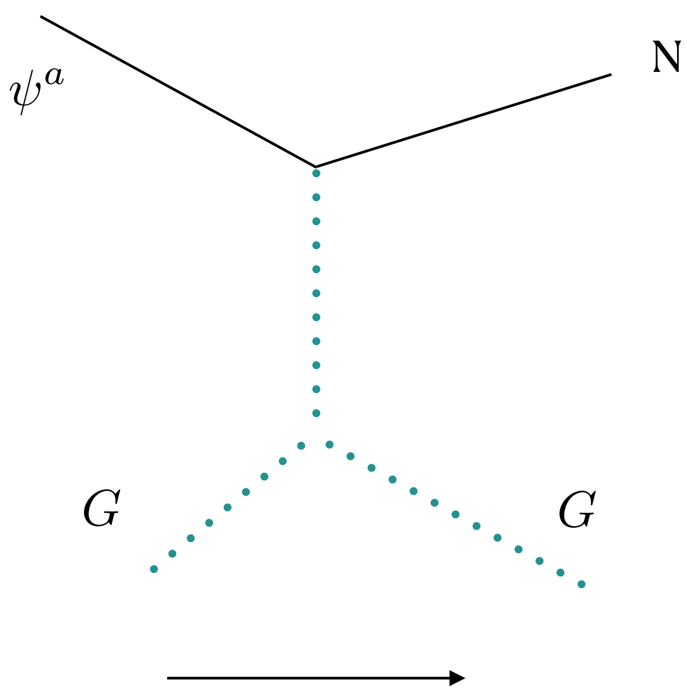
Fermions and hidden photons: $\mathcal{L} \supset \bar{\psi}\left(\gamma^\mu D_\mu + m\right)\psi$

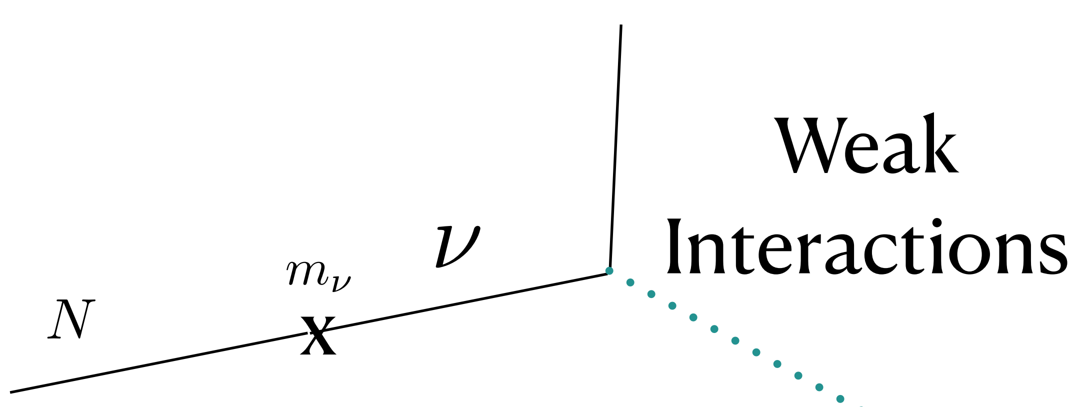
Hidden photon mixing with our photon: $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Fermions become milli-charged under E&M, while fundamental representation of non-abelian sector.
Also hot gas of hidden photons.

Right Handed Neutrinos

$$\mathcal{L} \supset \frac{1}{f_N} G^a_{\mu\nu} \psi^a \sigma^{\mu\nu} N$$





Efficient (i.e. during the current age of the universe) conversion of energy from dark glue into right handed neutrino

Thermalized population of right handed neutrinos at meV energies

At low energy (meV), conversion of N to neutrino is not suppressed! So N behaves like a thermalized population of neutrinos - at meV temperatures!

10x the temperature of CvB

Direct Detection

Challenge: Detect meV scale milli-charged particles

No existing experiments - but plenty of upcoming ideas (e.g. using EM cavities to search for milli-charged particles)

Challenge: Detect meV scale hidden photons.

Leverage work done for single IR photon detection, use work done for dark matter detection in this mass range

For neutrinos, this signal is significantly bigger than what PTOLEMY (tritium end point to detect CvB) looks for - but PLOLEMY is a very hard experiment

Interesting challenge for detection community!

Thank you!