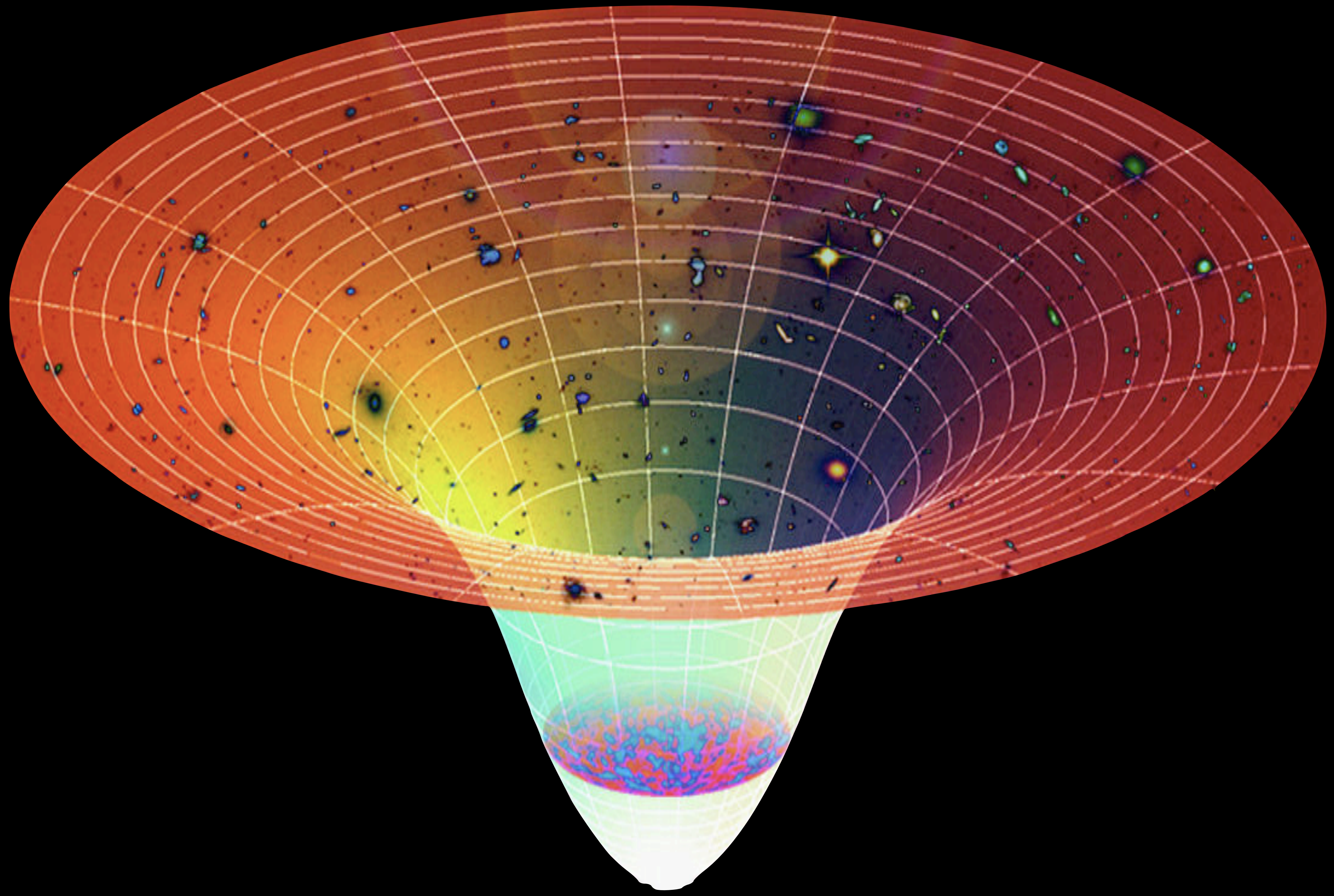
A Simple Self-Tuning Universe to Solve the Cosmological Constant Problem



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University of Edinburgh

Royal Observatory Edinburgh

Cosmological Frontiers in Fundamental Physics, Higgs Centre for Theoretical Physics, Edinburgh, 19-21 April 2024

- Self-tuning section based on

  Arnaz Khan & ANT,

  - *A Minimal Self-Tuning Scalar Field Model to Solve the Cosmological Constant Problem*, 2022, JCAP, 10, 075

  - *Structure formation and test of a Minimal Self-Tuning Universe*, 2024, in prep.

Arnaz Khan

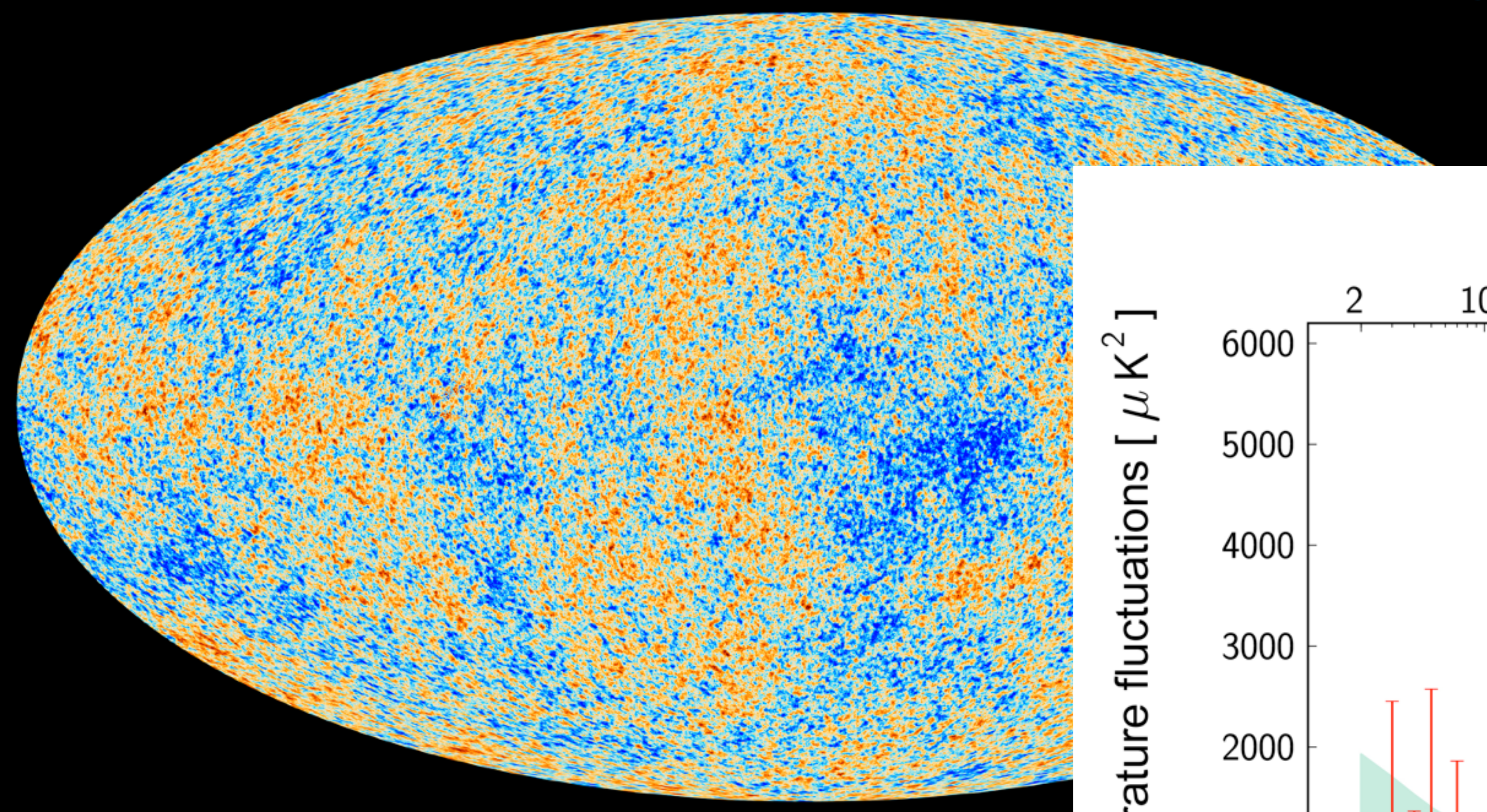
Lucas Lombriser

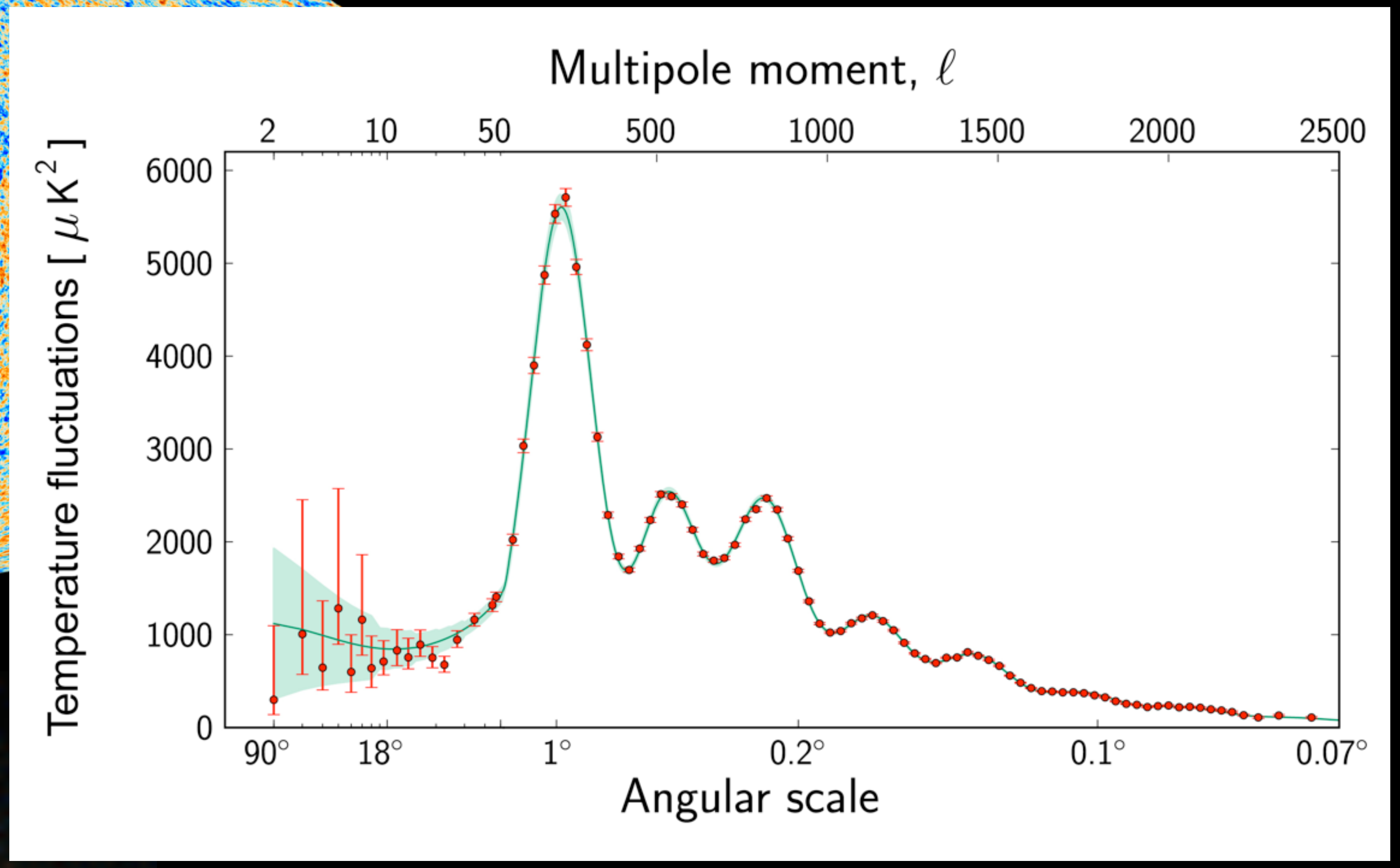
- Horndeski model work based on

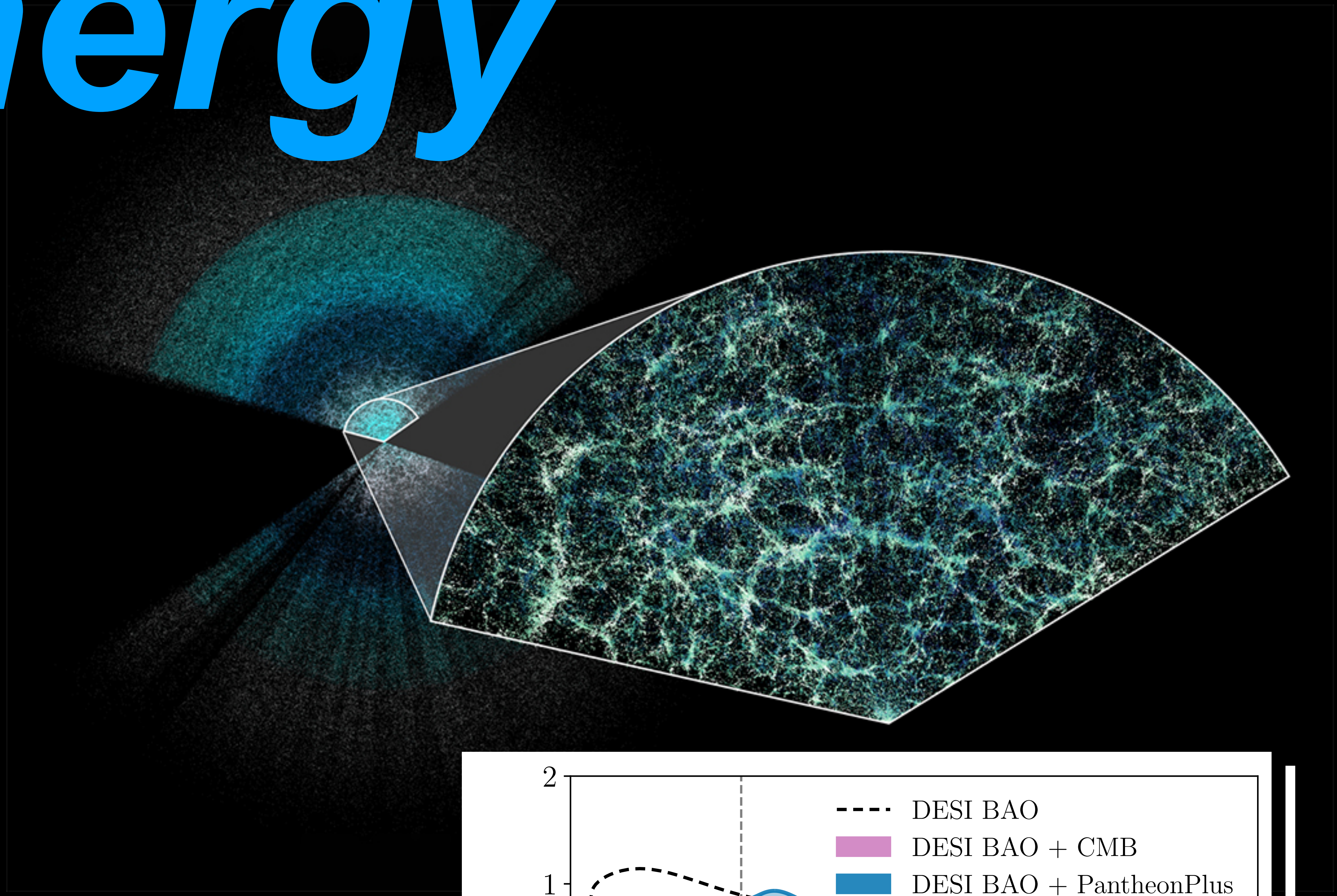
  Lucas Lombriser & ANT,
  Breaking a dark degeneracy with gravitational waves,
  2016, JCAP, 03, 31

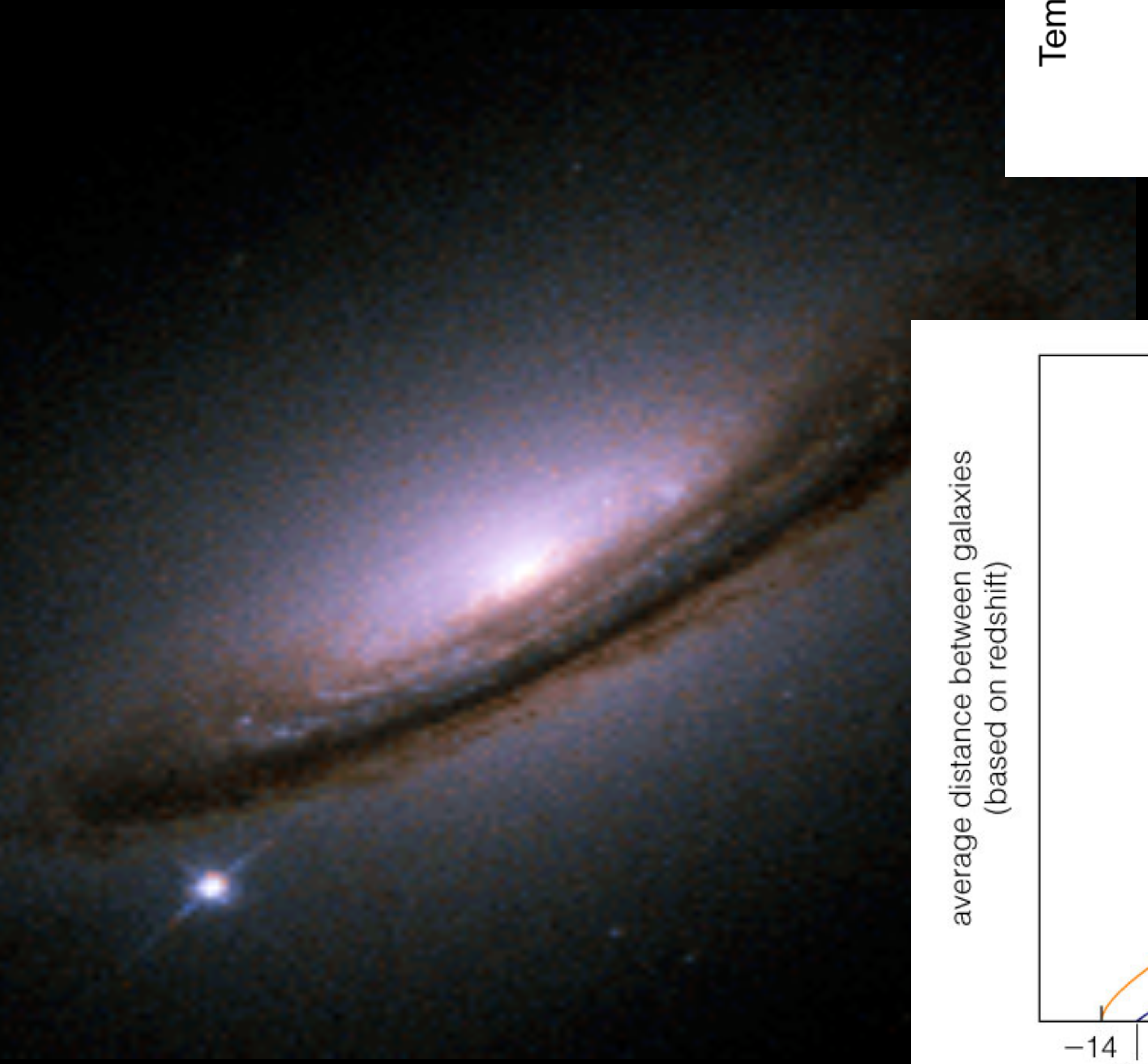
+ Euclid Consortium

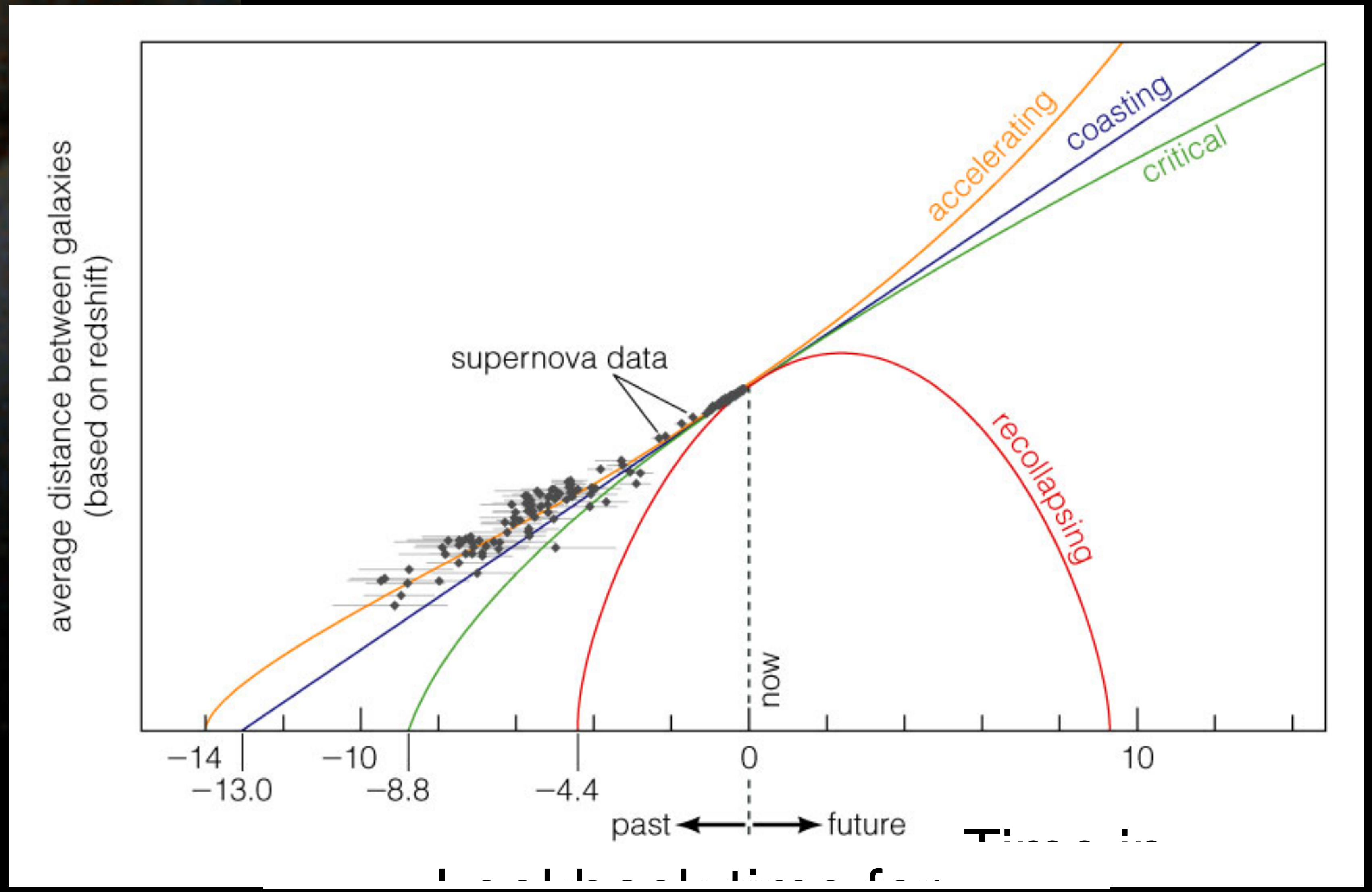
Dark Energy

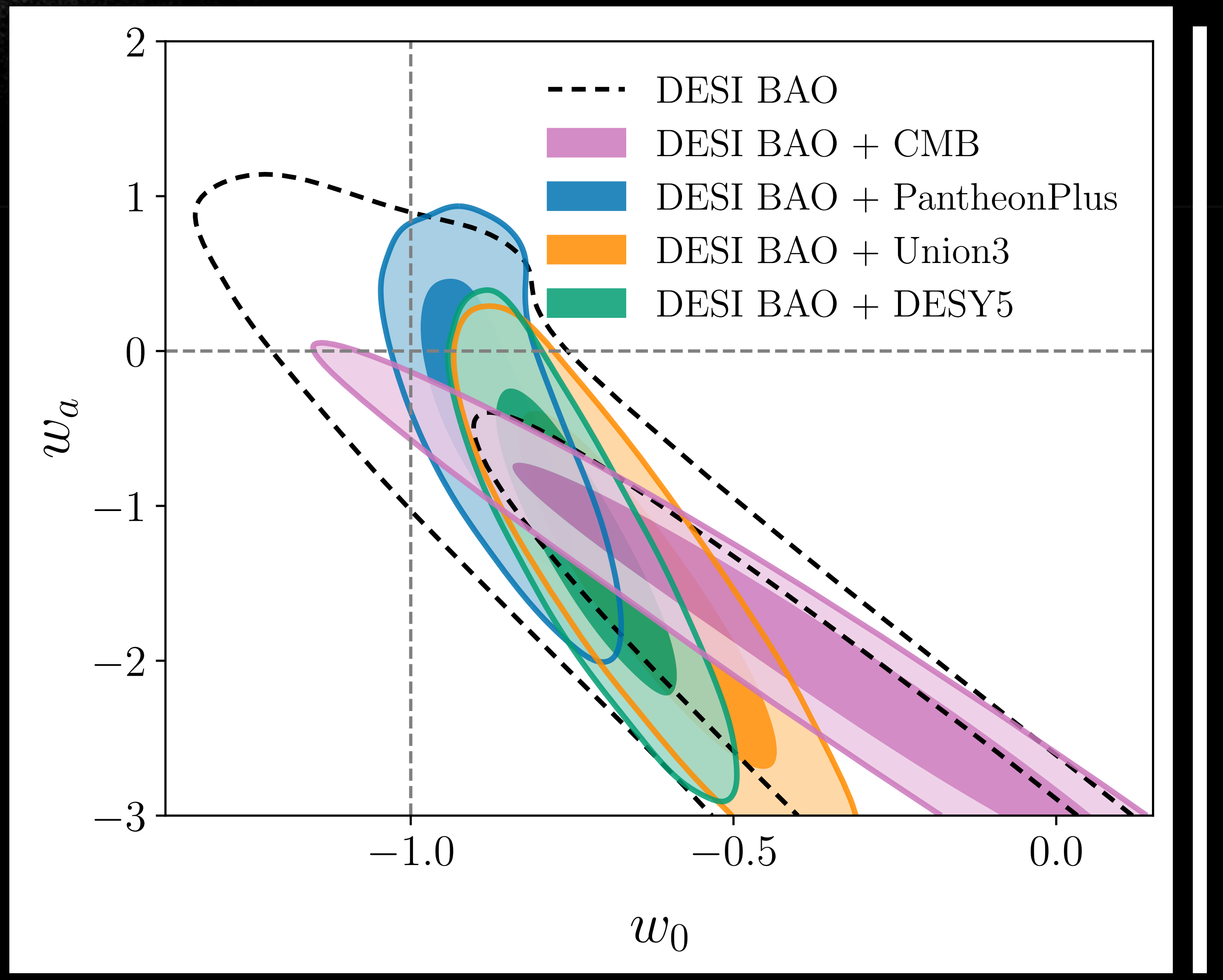



Multipole moment, ℓ
2 10 50 500 1000 1500 2000 2500
Temperature fluctuations [μK^2]
6000 5000 4000 3000 2000 1000 0
90° 18° 1° 0.2° 0.1° 0.07°
Angular scale






average distance between galaxies
(based on redshift)
accelerating
coasting
critical
supernova data
recollapsing
now
−14 −10 0 10
−13.0 −8.8 −4.4
past future


DESI BAO
DESI BAO + CMB
DESI BAO + PantheonPlus
DESI BAO + Union3
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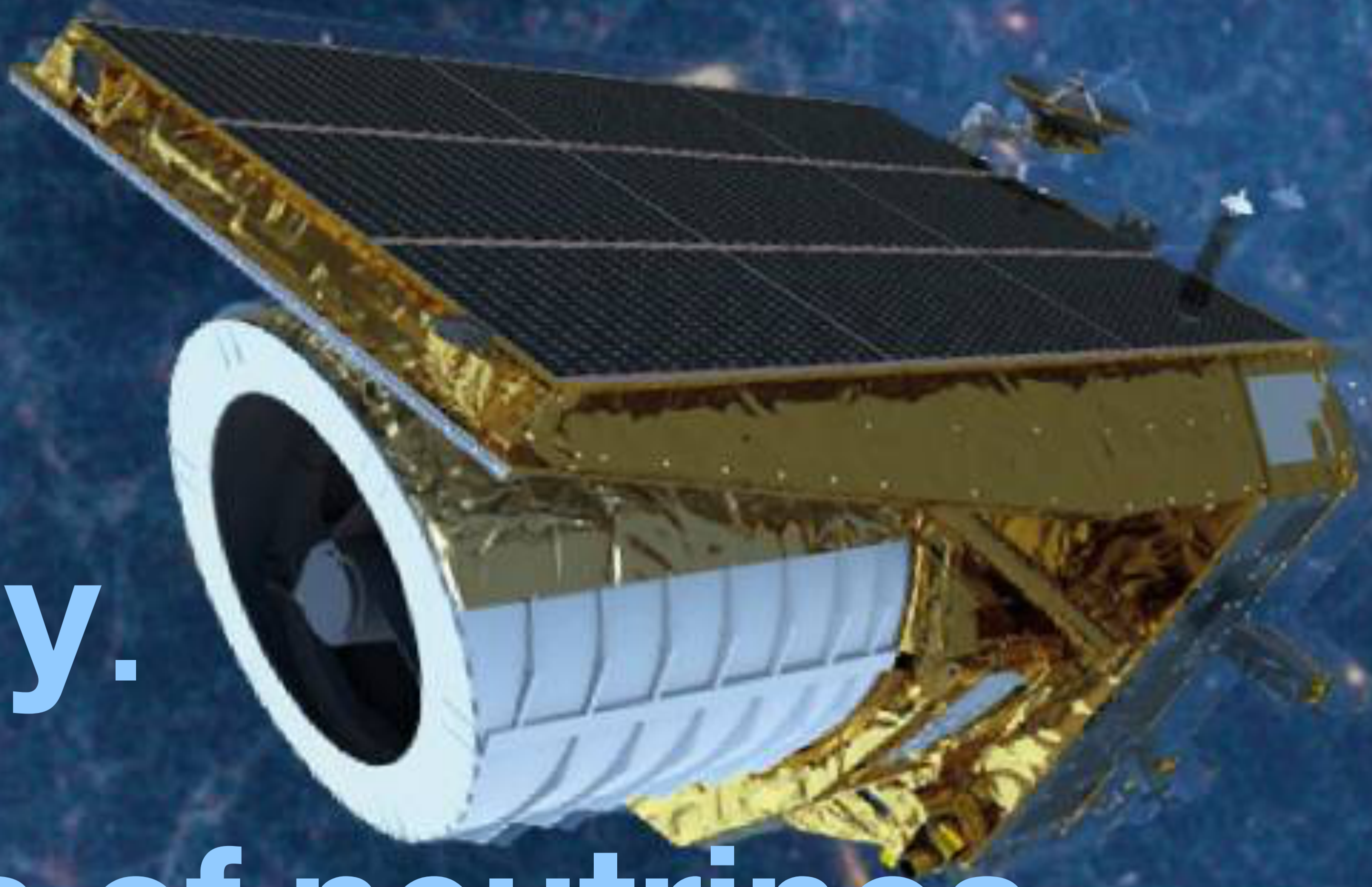
w_a
2 1 0 −1 −2 −3
−1.0 −0.5 0.0
w_0

Euclid's Dark Energy Mission

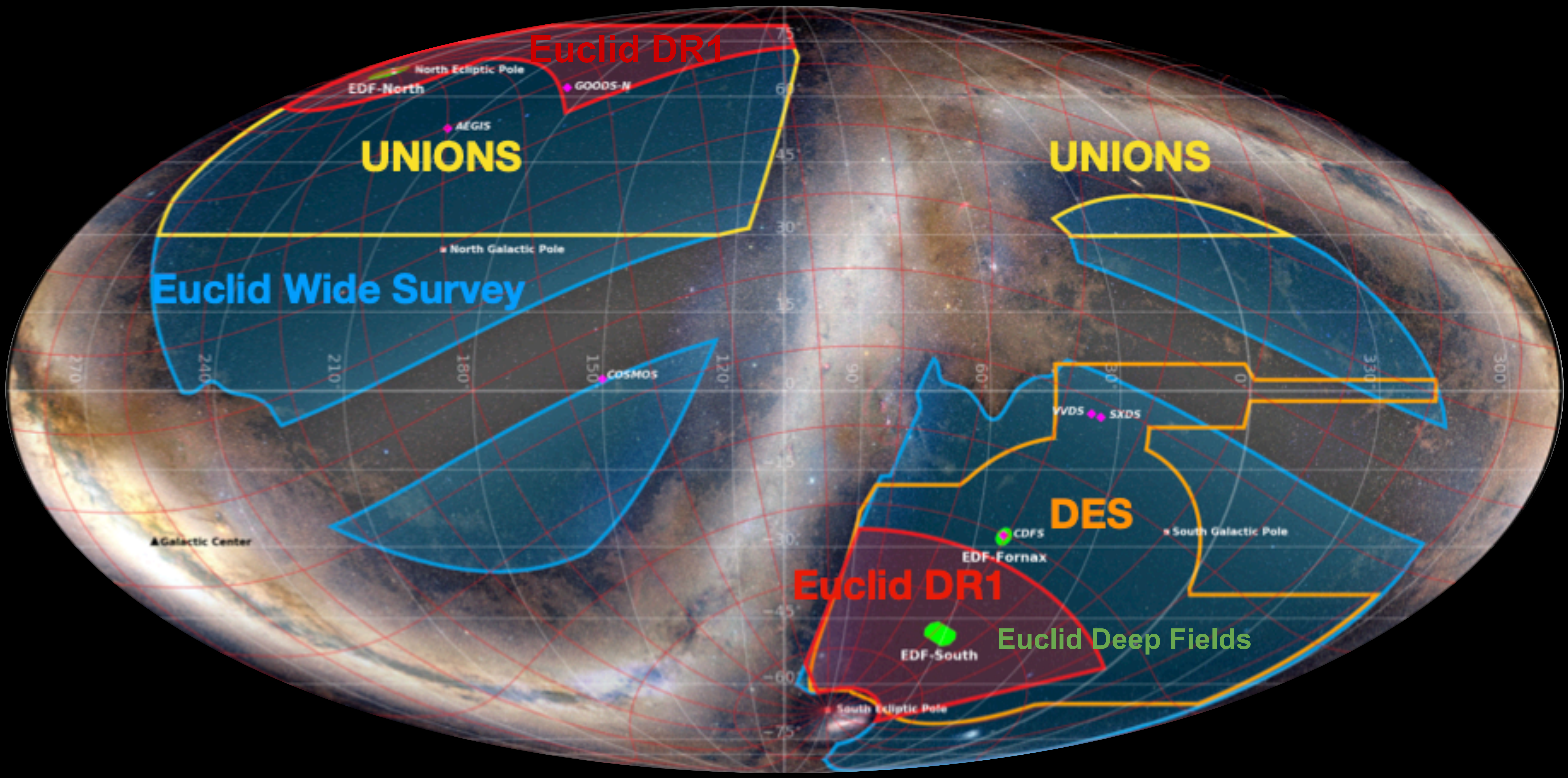


- Measure the properties of **Dark Energy**.
- Probe **Dark Matter** and measure the **mass of neutrinos**.
- **Test Einstein's Theory of Gravity** on the largest scales.
- Probe the **very earliest moments** of the Universe.

Euclid Satellite and Launch

Euclid's Dark Energy Survey

- Map 1/3rd of the sky with Weak Lensing and Galaxy Clustering.
- High-quality optical images & 8-colour distances for 1.5 Billion galaxies.
- Measure 35 Million spectroscopic distances.



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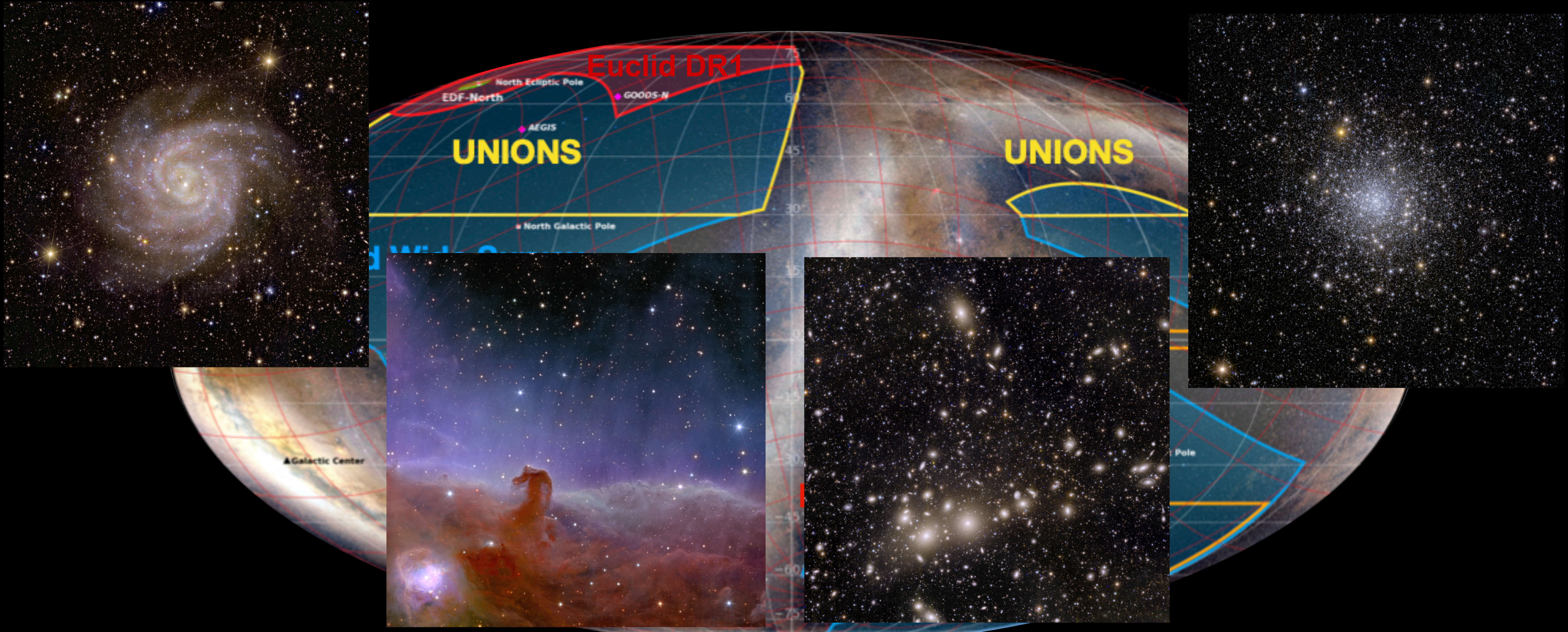
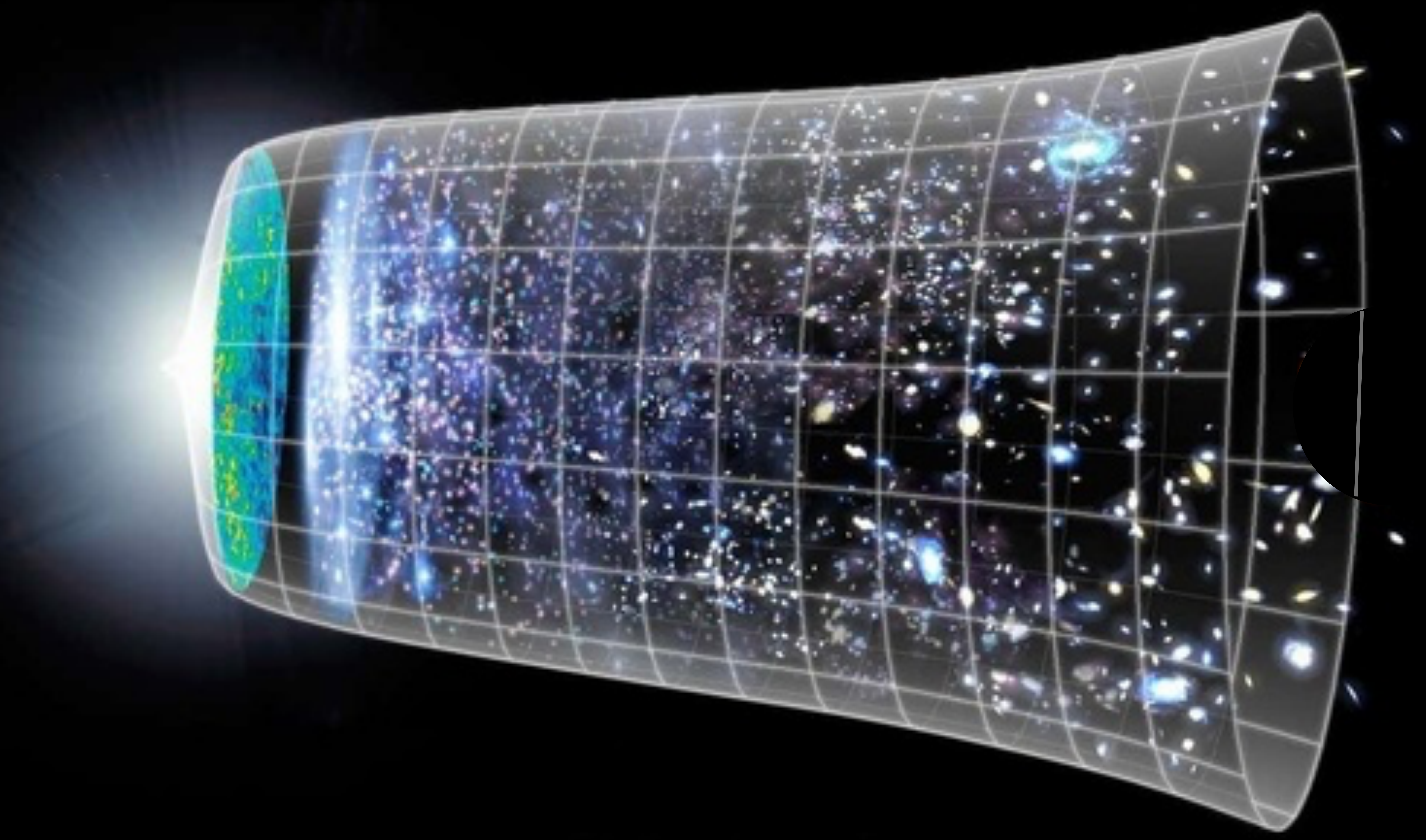
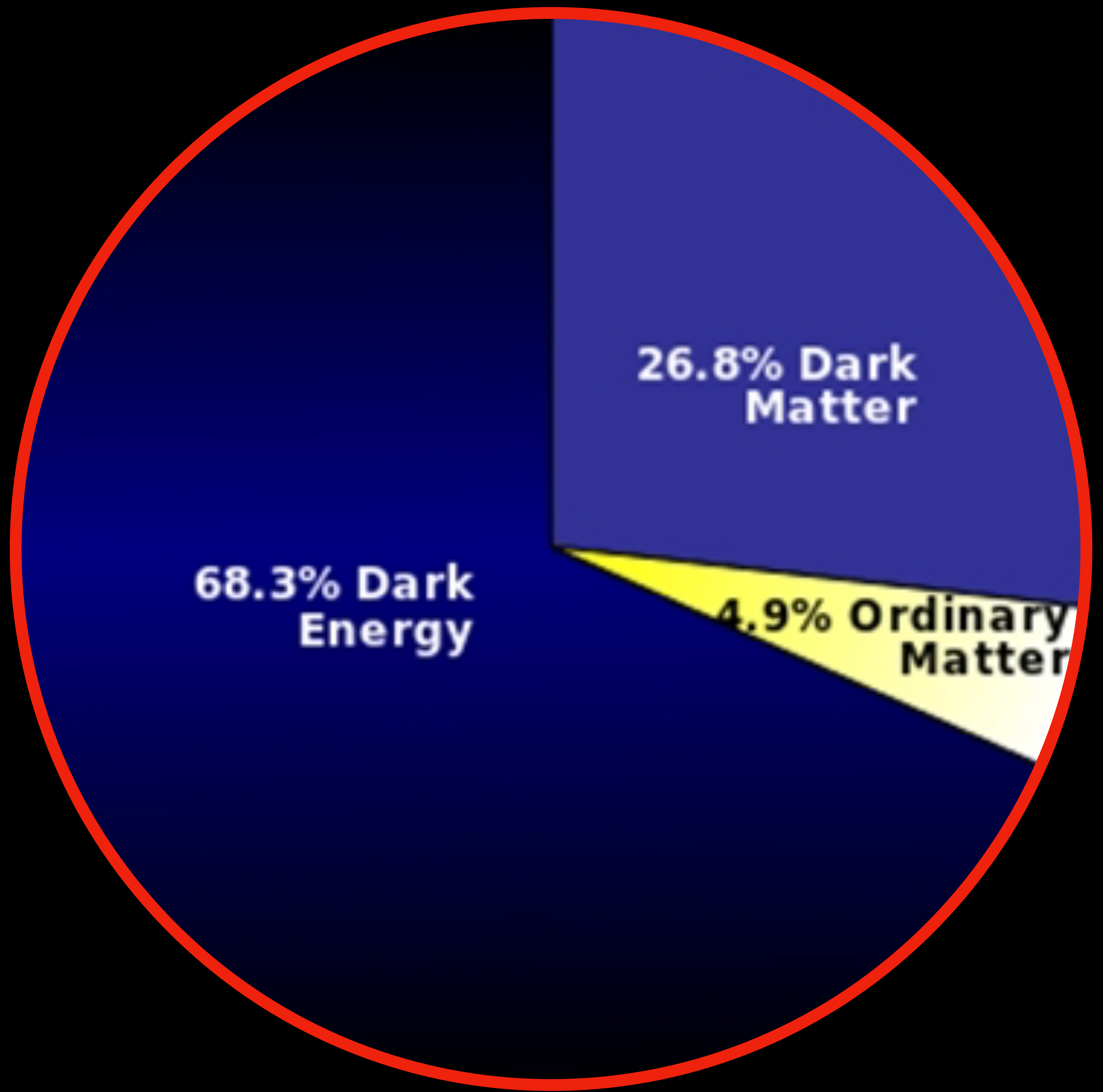


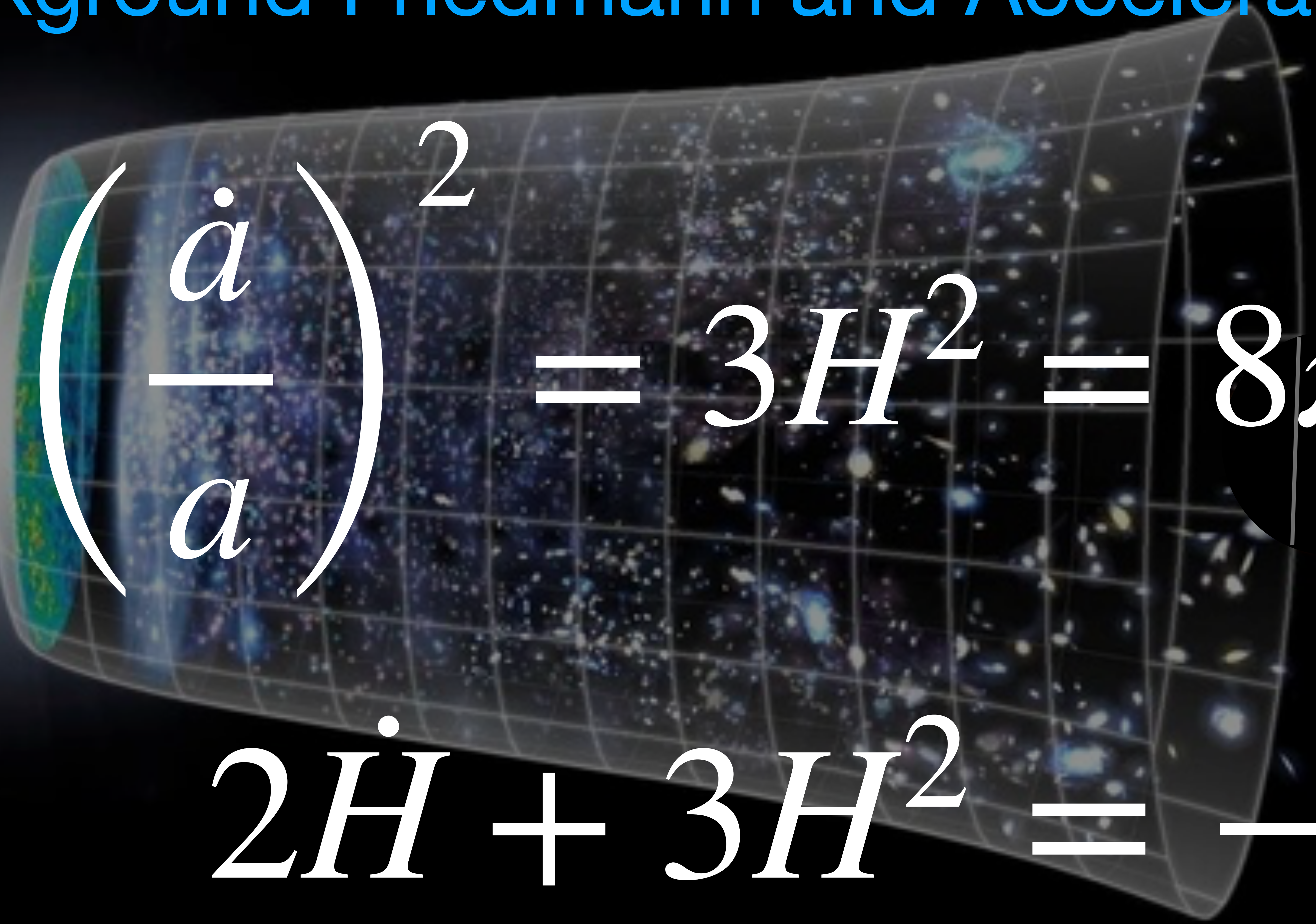
Standard Cosmological Model

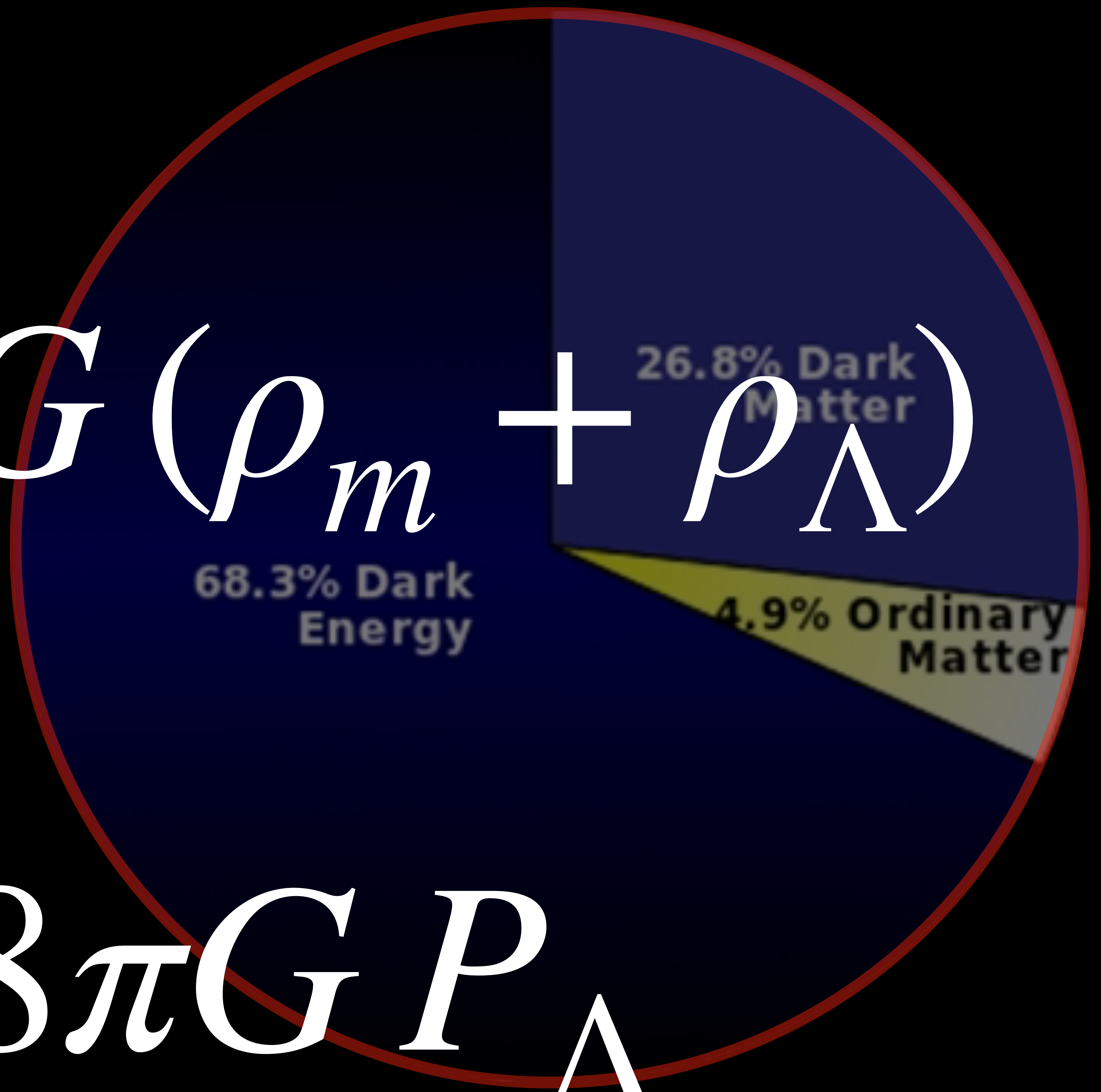




Standard Cosmological Model

Background Friedmann and Acceleration Equations





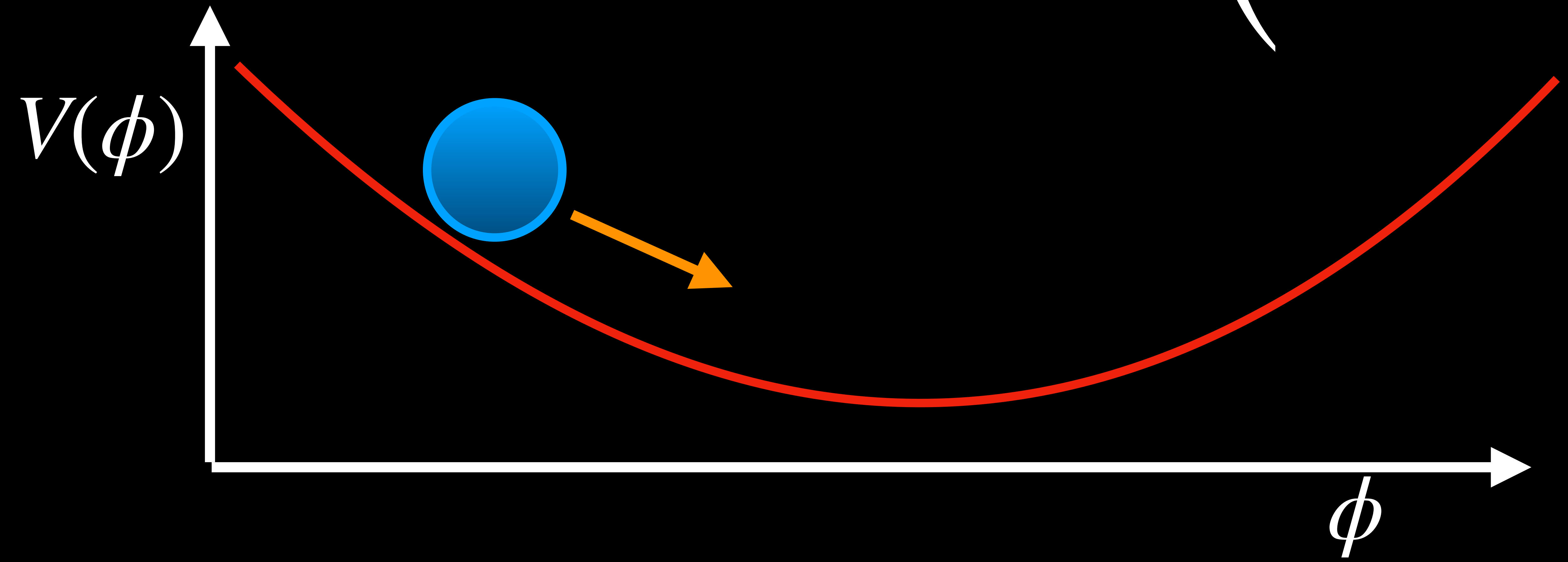
$$3\left(\frac{\dot{a}}{a}\right)^2 = 3H^2 = 8\pi G\,(\rho_m + \rho_\Lambda)$$

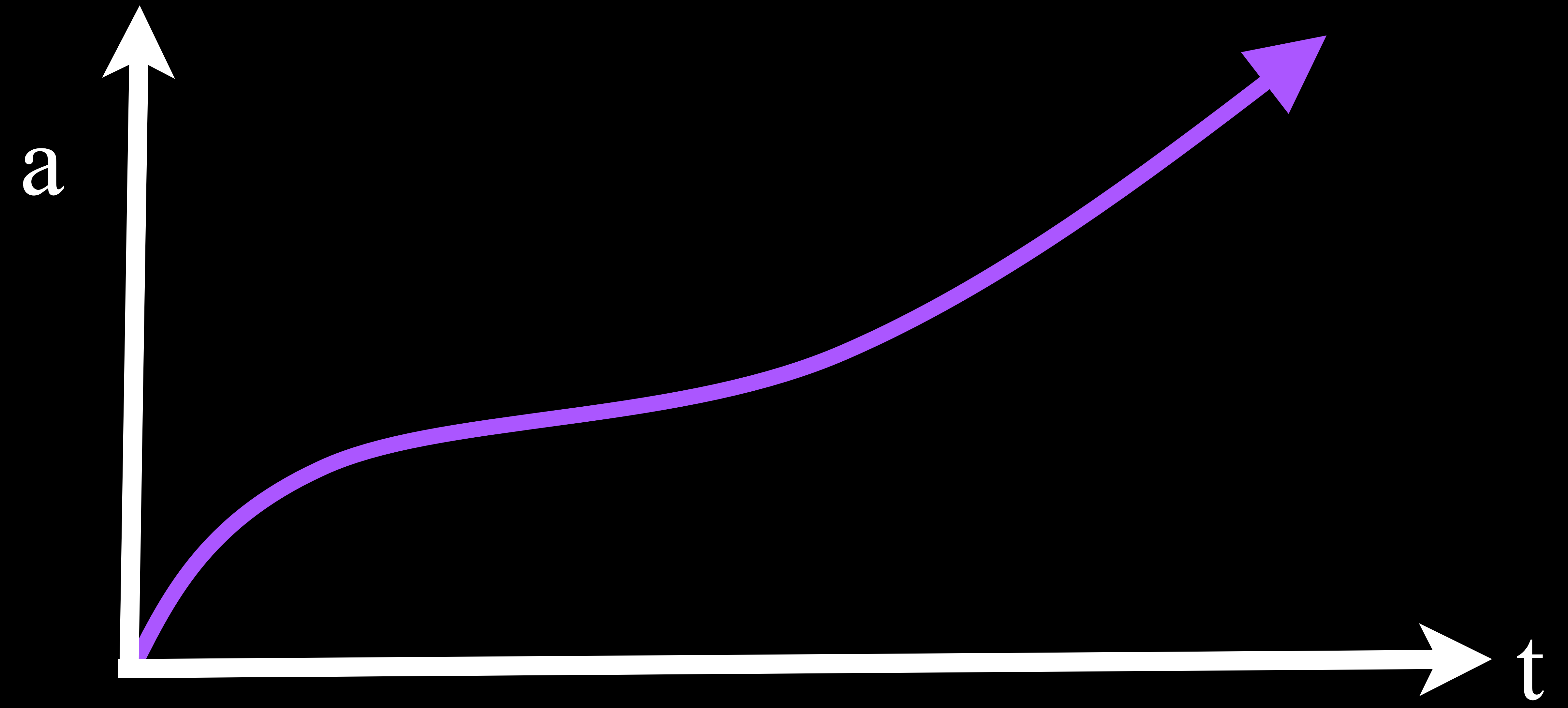
$$2\dot{H} + 3H^2 = -\,8\pi G\,P_\Lambda$$

Scalar Field Dark Energy

We can replace ρ_Λ with something dynamical, like Inflation -

$$3H^2 = 8\pi G\left(\rho_m + \dot{\phi}^2/2 + V(\phi)\right)$$





Acceleration ($H = \text{const}$) if

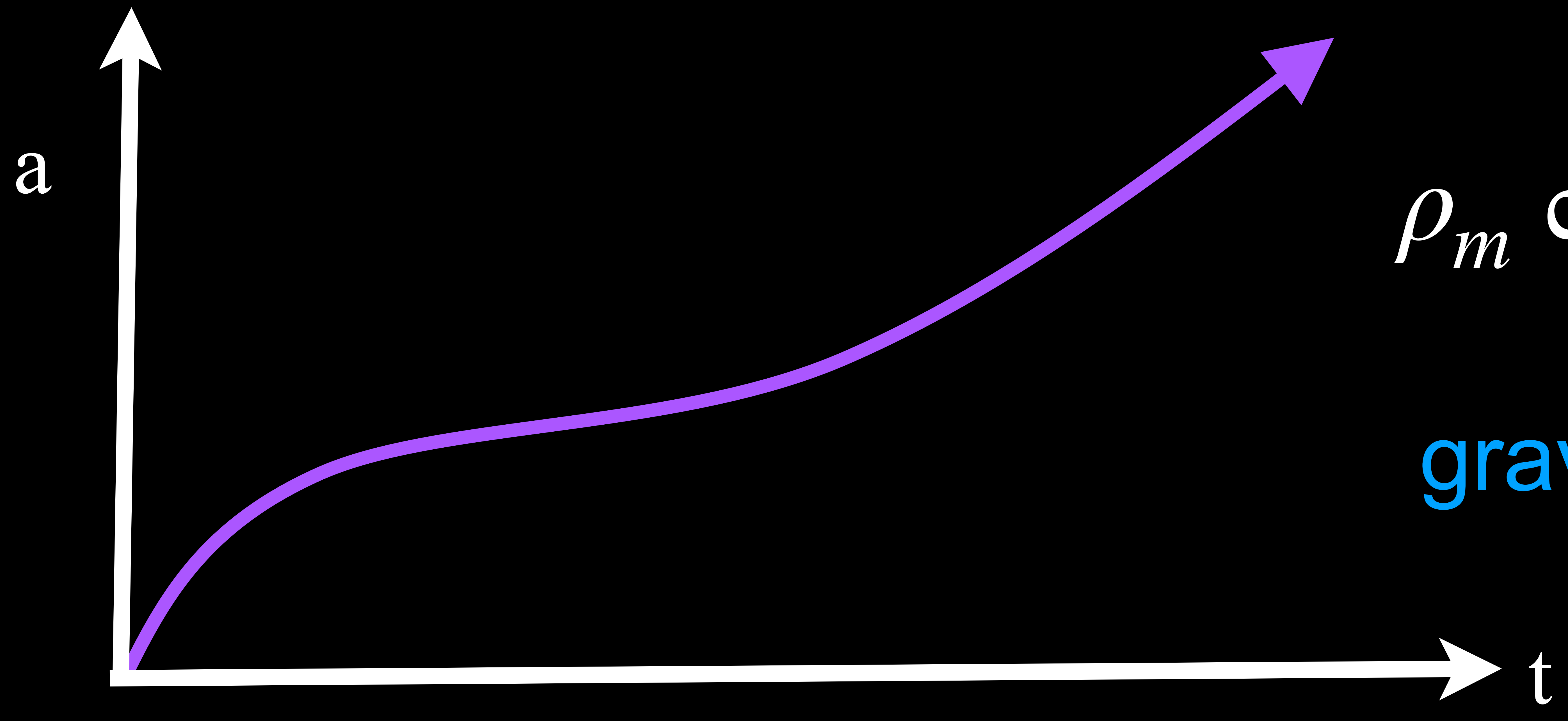
ρ_m and $\dot{\phi}^2 \ll V(\phi) \approx \text{const.}$

Scalar Field Modified Gravity

Can also modify gravity to get acceleration:

$$3H^2(\phi + \phi') = 8\pi G\rho_m$$

$$\phi' = \frac{d\phi}{d\ln a}$$

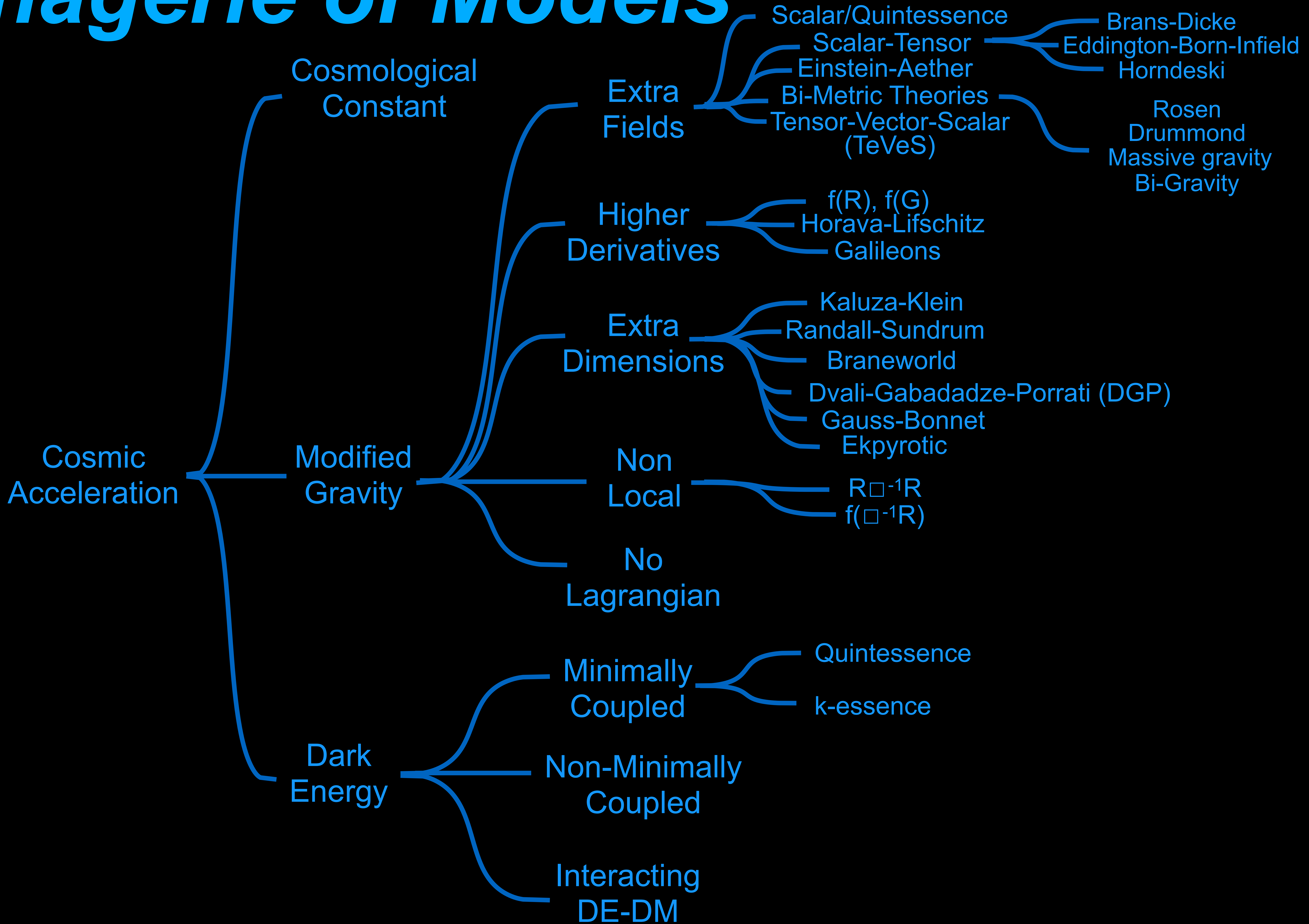


$\rho_m \propto a^{-3}$, so if field decays as

$$\phi \propto a^{-3}$$

gravity gets stronger & we get acceleration.

A Menagerie of Models



Scalar-Tensor Theories

- **Horndeski Theory** (1974) is the most general scalar-tensor theory which maps to many dark energy and modified gravity models:

$$\mathscr{L} = G_4(\phi, X)R + G_3(\phi, X)\Box\phi + G_2(\phi, X)$$

$$+2G_{4X}(\phi, X)[(\Box\phi)^2 - (\nabla^\mu\nabla^\nu\phi)^2] + G_5(\phi, X)\,G_{\mu\nu}\nabla^\mu\nabla^\nu\phi$$

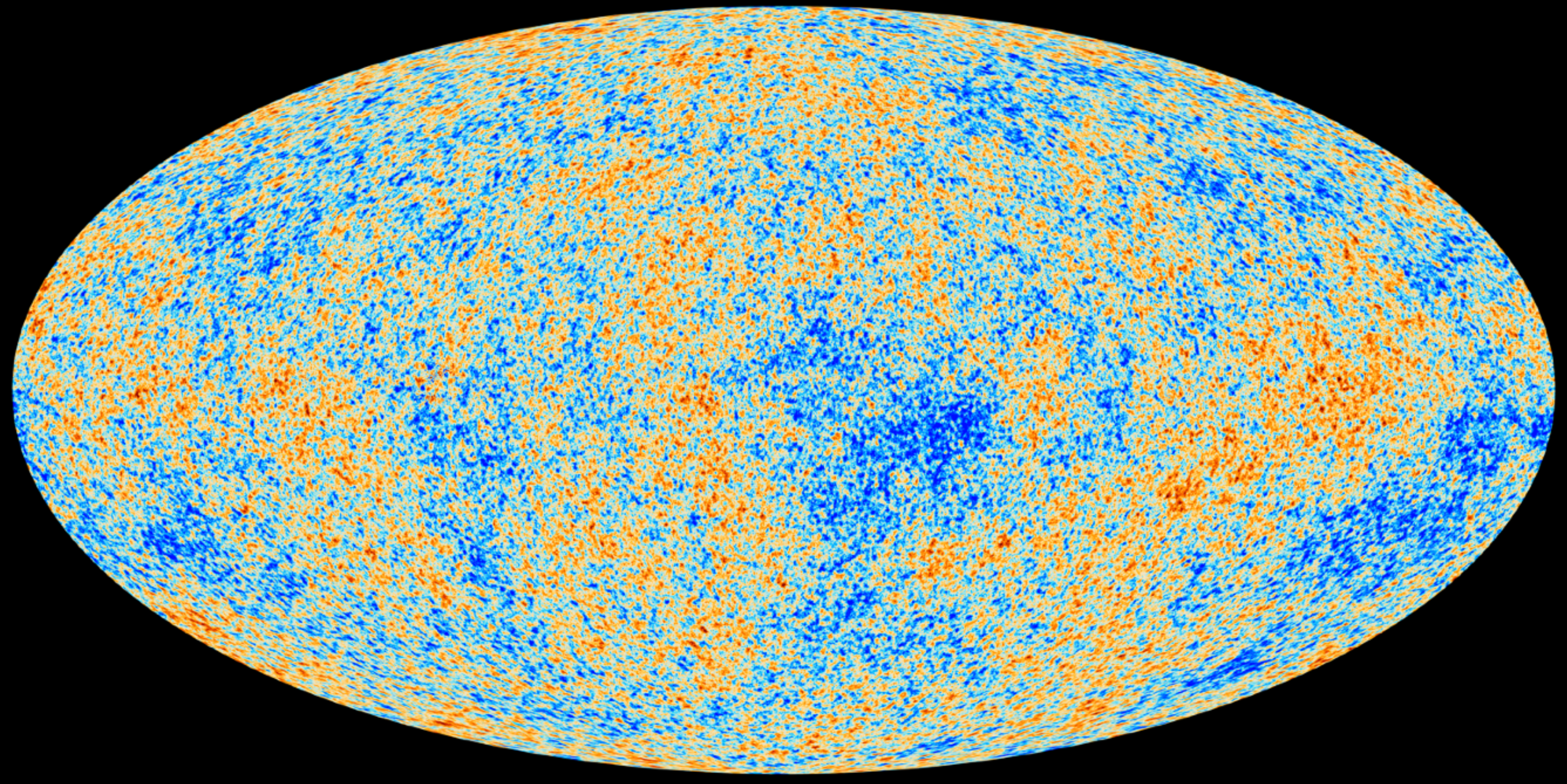
$$-\frac{1}{6}G_{5X}(\phi, X)[(\Box\phi)^3 - 3\Box\phi(\nabla^\mu\nabla^\nu\phi)^2 + 2(\nabla^\mu\nabla^\nu\phi)^3]$$

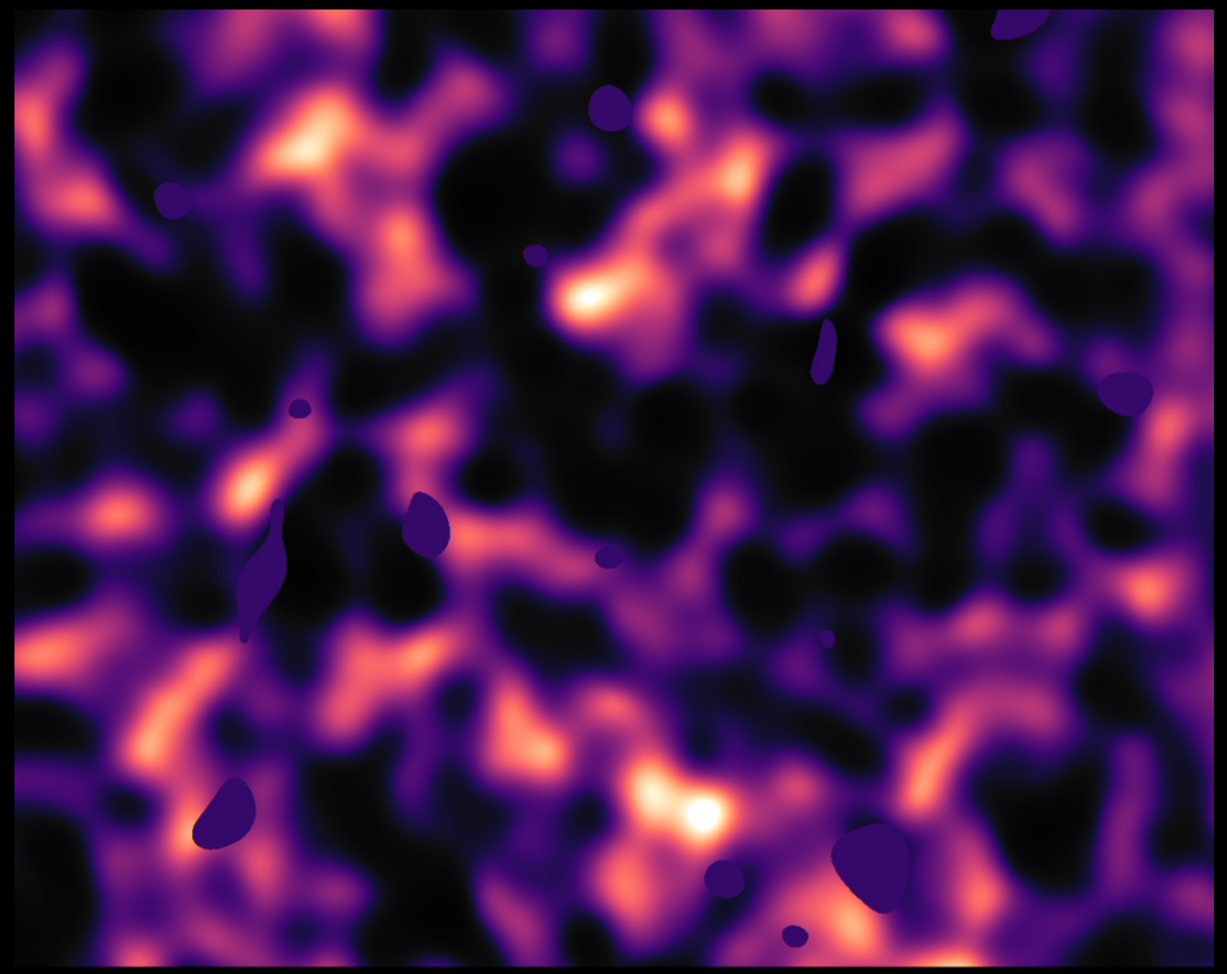
$$X = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

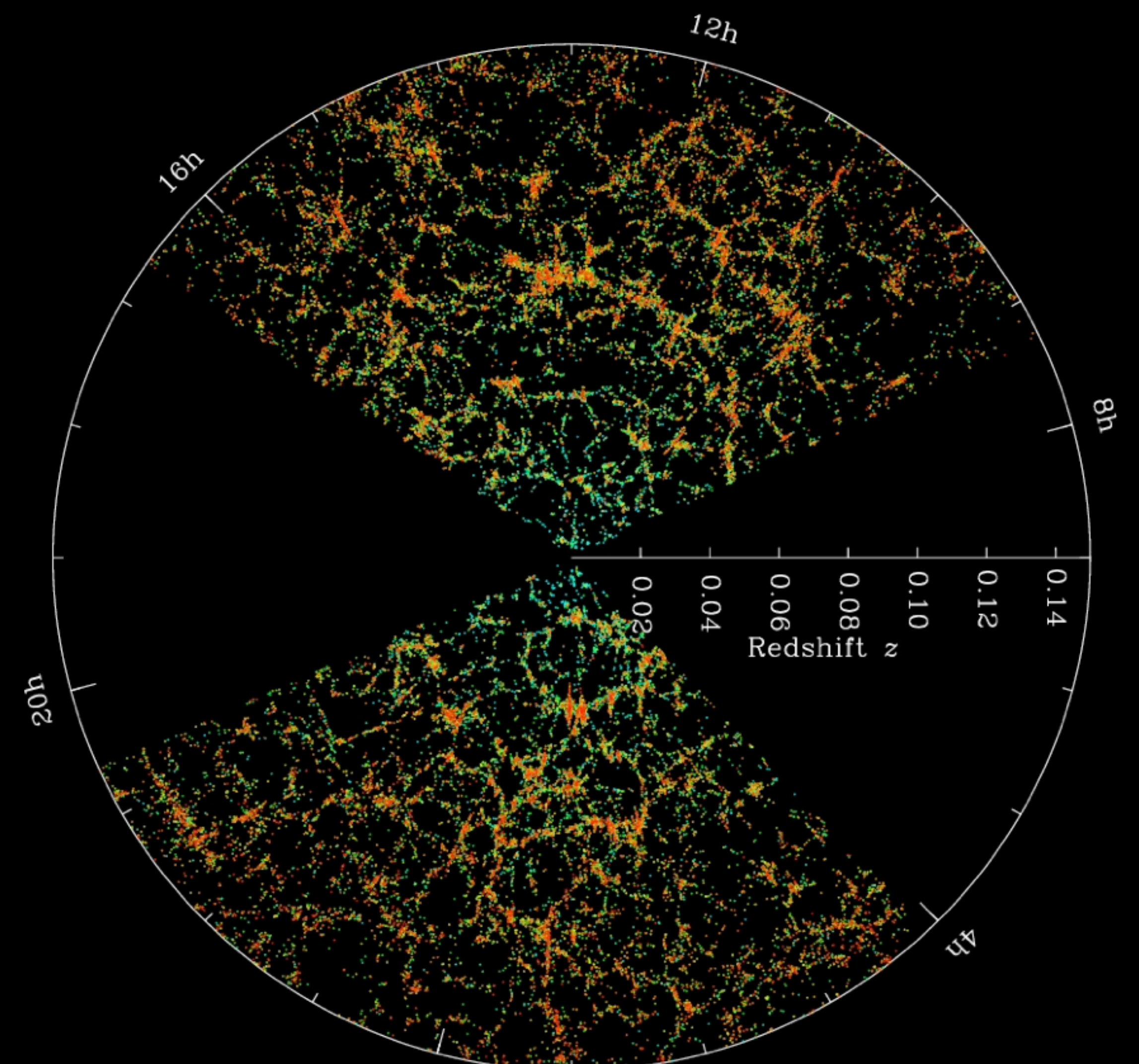
- But a monster !!!

Constraining Horndeski

- Simplify Horndeski Theory for background cosmology and linear perturbations.







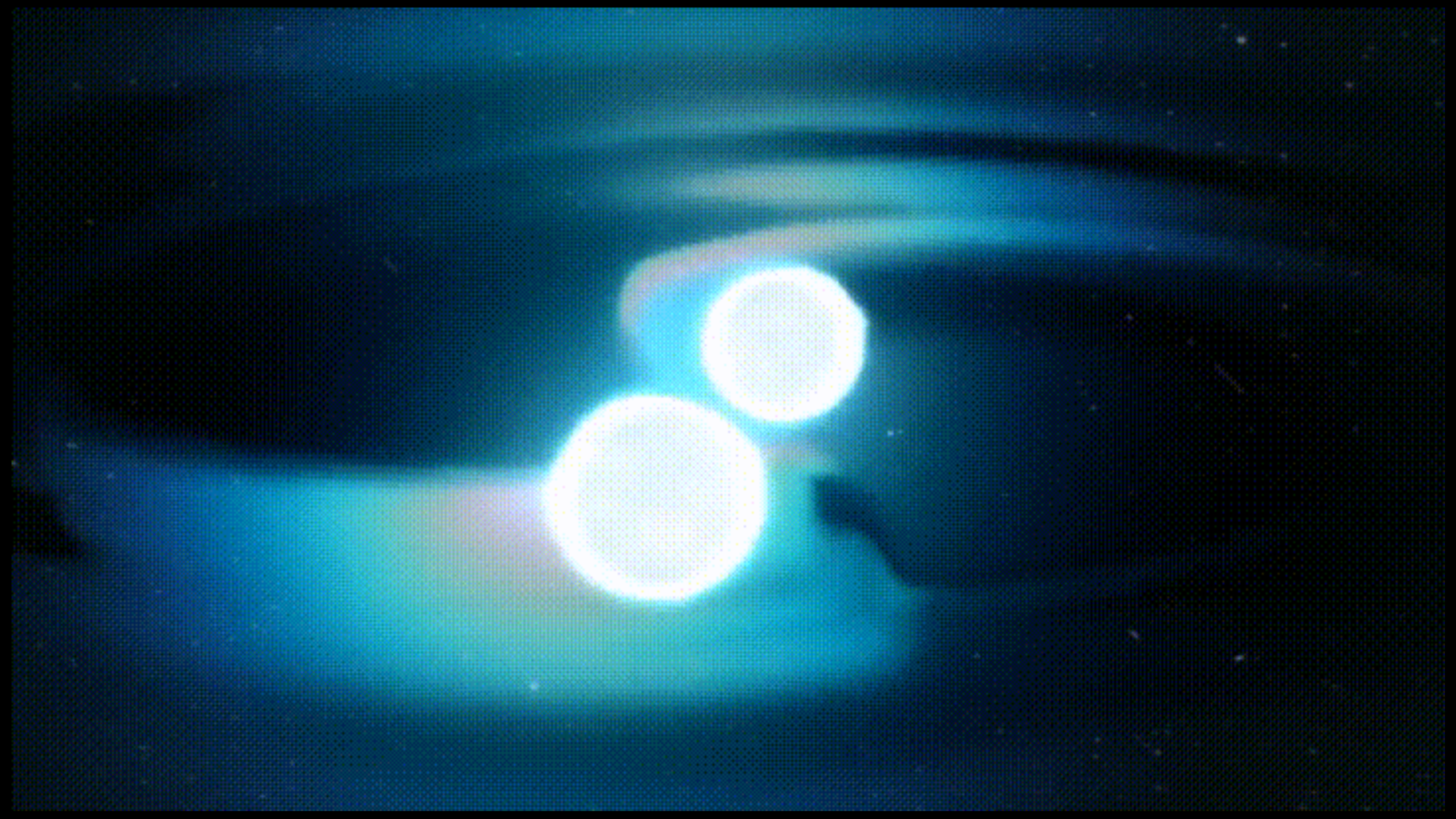
- But too much freedom to be constrained by cosmological observations - by one free function (Lombriser & ANT, 2016).

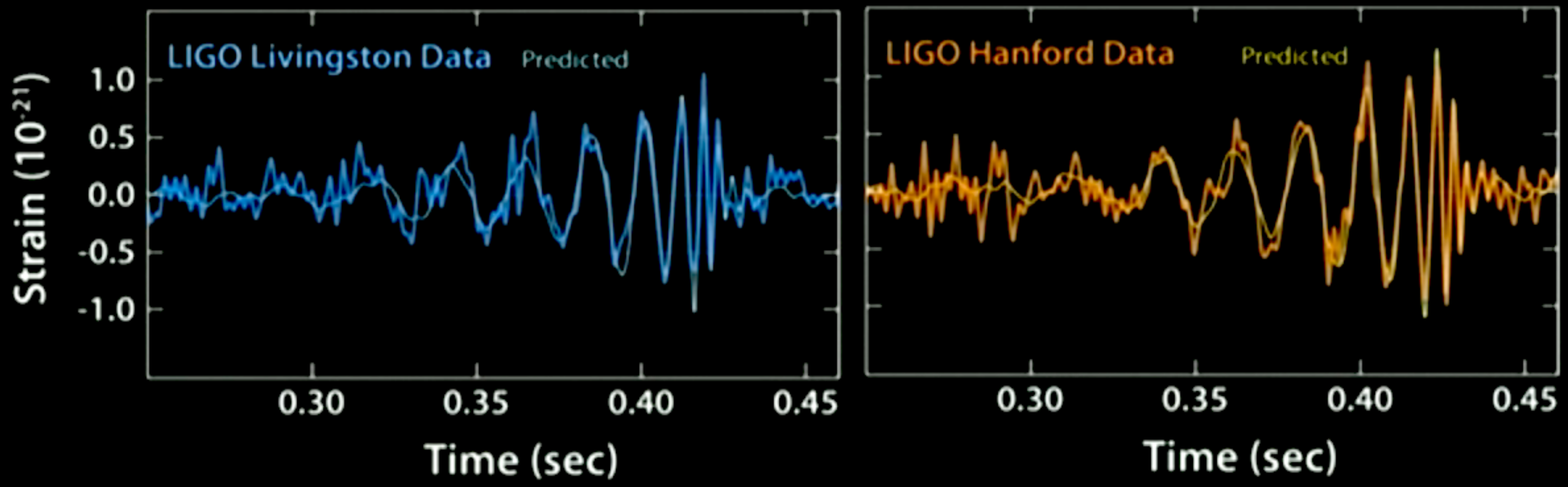
- Can choose this function to be the speed of gravitational waves, c_T.

- Can measure GW and EM signal from merging neutron stars.

Constraining Horndeski

- GW speed measured by GW170817 LIGO/Virgo + FERMi/Integral detections of GW and EM signal.





- Reduces Horndeski model-space to

$$\mathscr{L} = G_4(\phi, X)R + G_3(\phi, X)\Box\phi + G_2(\phi, X)$$

Lombriser & Taylor (2016), Baker et al. (2017), Creminelli & Vernizzi (2017), Sakstein & Jain (2017), Skater et al (2017), Nojiri & Odinstov (2017), Jana et al (2017), Amendola et al (2017), Crisostomi & Koyaman (2017), Langois et al (2017),…..

Constraining Dark Energy Models

- So we can now constrain remaining Horndeski Dark Energy models with cosmological data,

$$\mathcal{L} = G_4(\phi, X)R + G_3(\phi, X)\Box\phi + G_2(\phi, X)$$

- Can further constrain G_4 - Lombriser & ANT 2016.

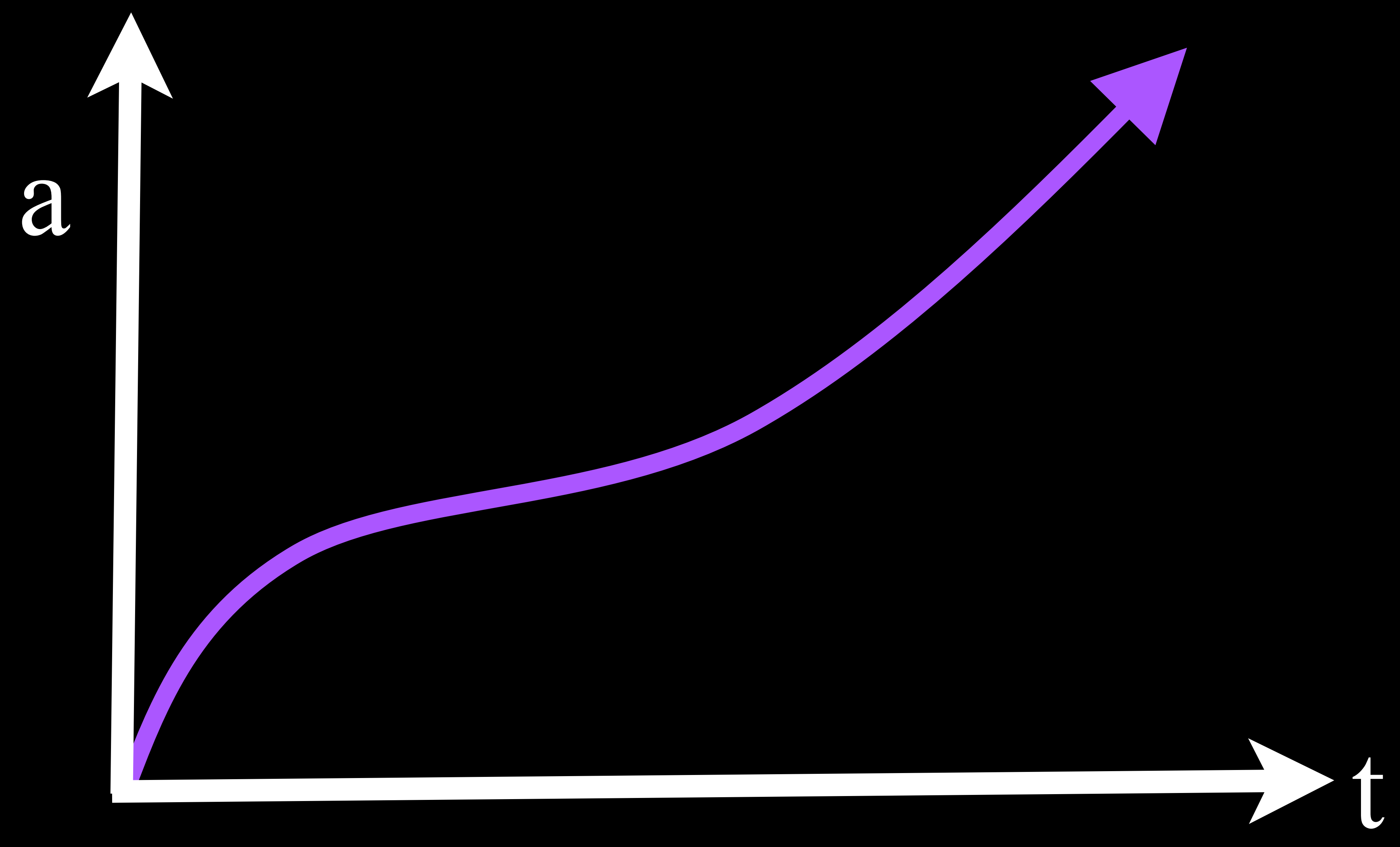
- But still a large model space.
- Can parameterise the background expansion (w_0, w_a) and perturbations (forces and sound speed) to test - ***Euclid***!

  - **We can also look for models which solve fundamental problems - e.g. the Cosmological Constant Problem.**

The Cosmological Constant Problem

- A natural candidate for Dark Energy is vacuum energy,

$$3H^2 = 8\pi G \left(\rho_m + \rho_{\text{vac}}\right)$$



- The vacuum has contributions from Einstein's Cosmological Constant and quantum zero-point vacuum energy

$$\rho_{\text{vac}} = \rho_\Lambda + \rho_{\text{QM}}$$

The Cosmological Constant Problem

$$\rho_{\text{vac}} = \rho_{\Lambda} + \rho_{\text{QM}}$$

- Dimensionally,

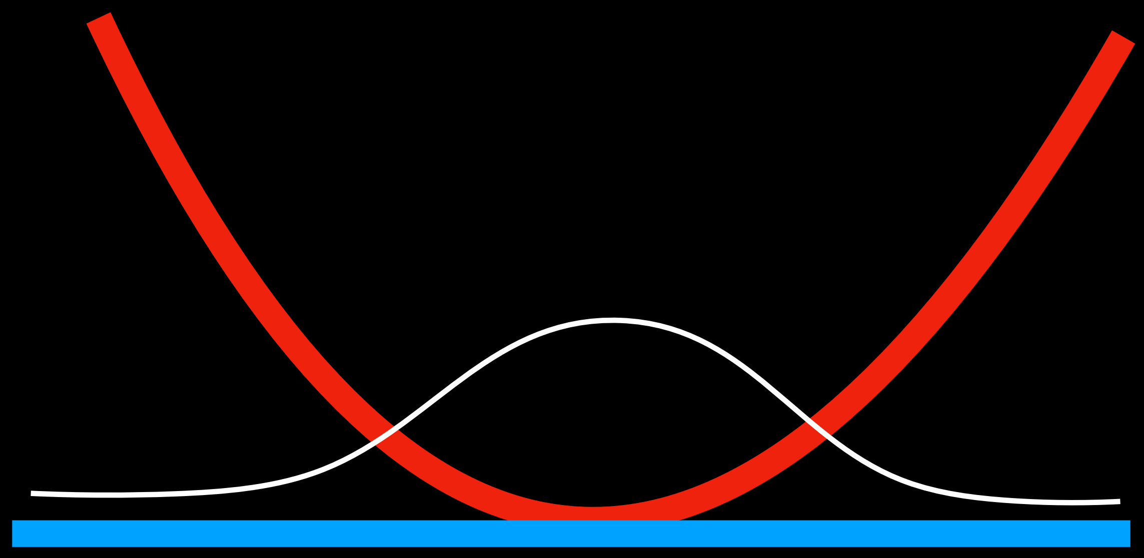
$$\rho_{\Lambda} \sim G^{-2} \sim M^4_{\text{Planck}} \sim 10^{120} \rho_{\text{Obs}}$$

- Or we can assume ρ_{Λ} is a second free parameter in gravity (the *Let's All Go Home* Conjecture).

The Cosmological Constant Problem

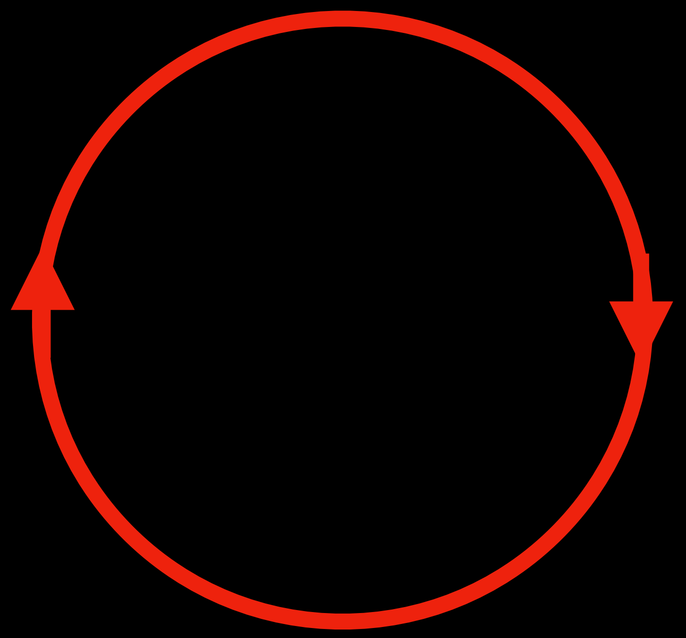
$$\rho_{\text{vac}} = \rho_\Lambda + \rho_{\text{QM}}$$

- In Quantum Field Theory we should be able to calculate the vacuum energy, from the zero-point energy of a quantum harmonic oscillator



$$\rho_{\text{QM}} = \frac{1}{2}\int \frac{d^3k}{(2\pi)^3}\sqrt{k^2+m^2}$$

$$\sim m^4 \ln(m^2/\mu^2) \sim 10^{54}\rho_{\text{Obs}}$$

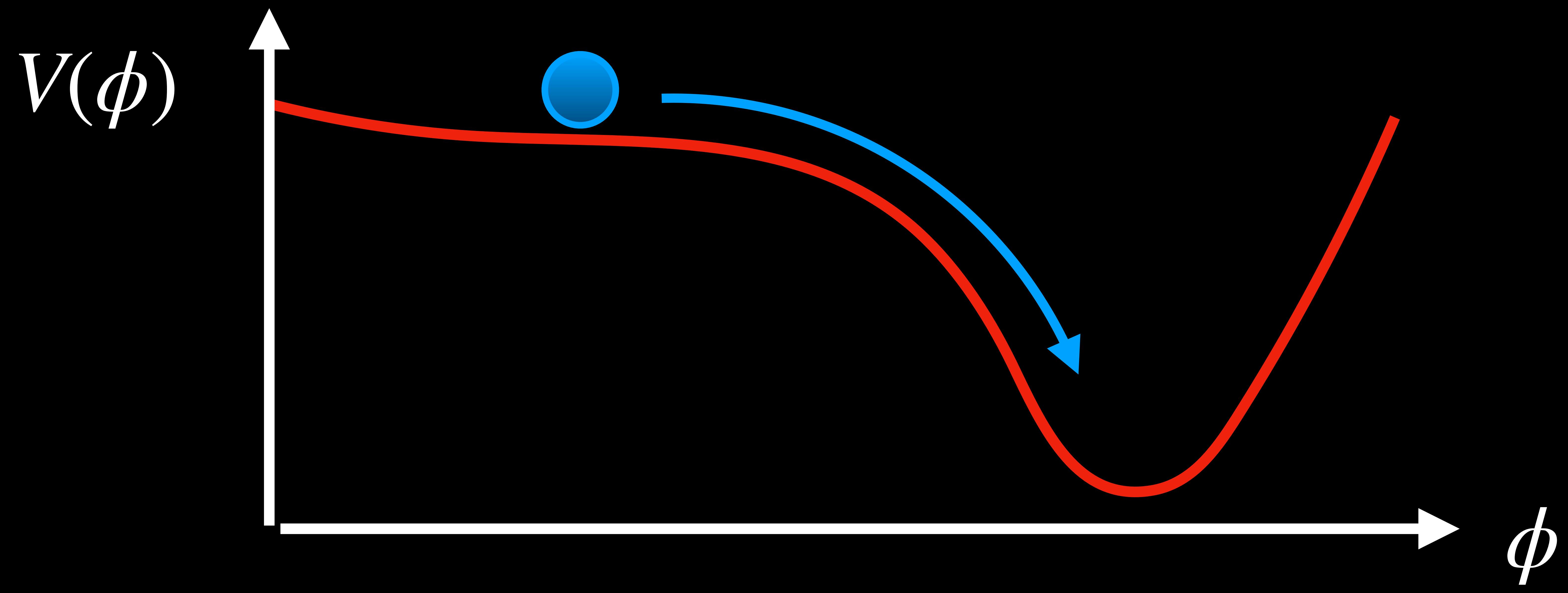


- But there are higher order terms, new massive particles,....

The Cosmological Constant Problem

$$\rho_{\text{vac}} = \rho_\Lambda + \rho_{\text{QM}} + \rho_{PT}$$

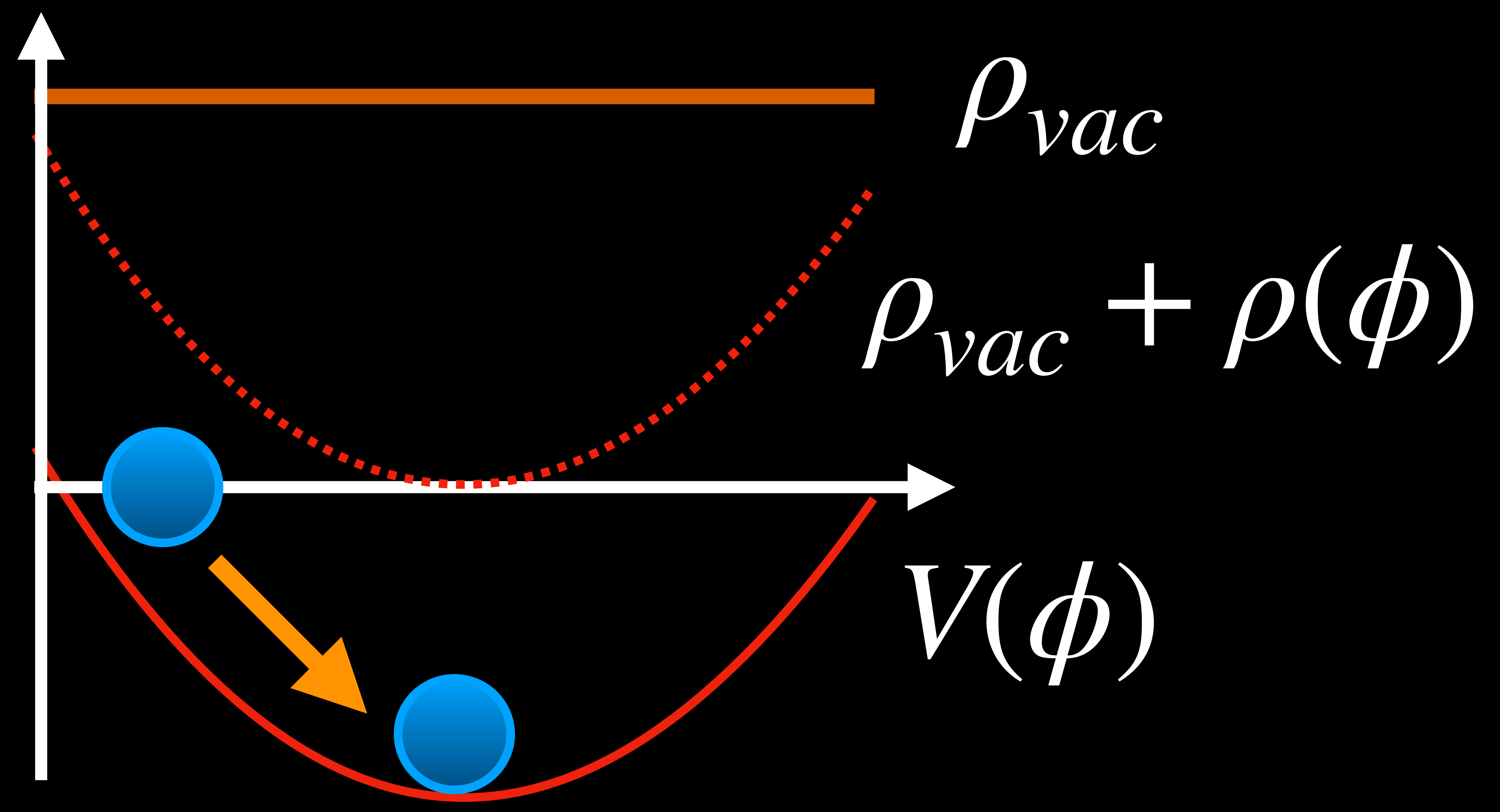
- Also need to account for Phase Transitions



The Cosmological Constant Problem

- Vacuum energy resistant to Renormalisation - too unstable.
- Is there a physical mechanism to explain a small vacuum energy?

- Can a field cancel a large Cosmological Constant?



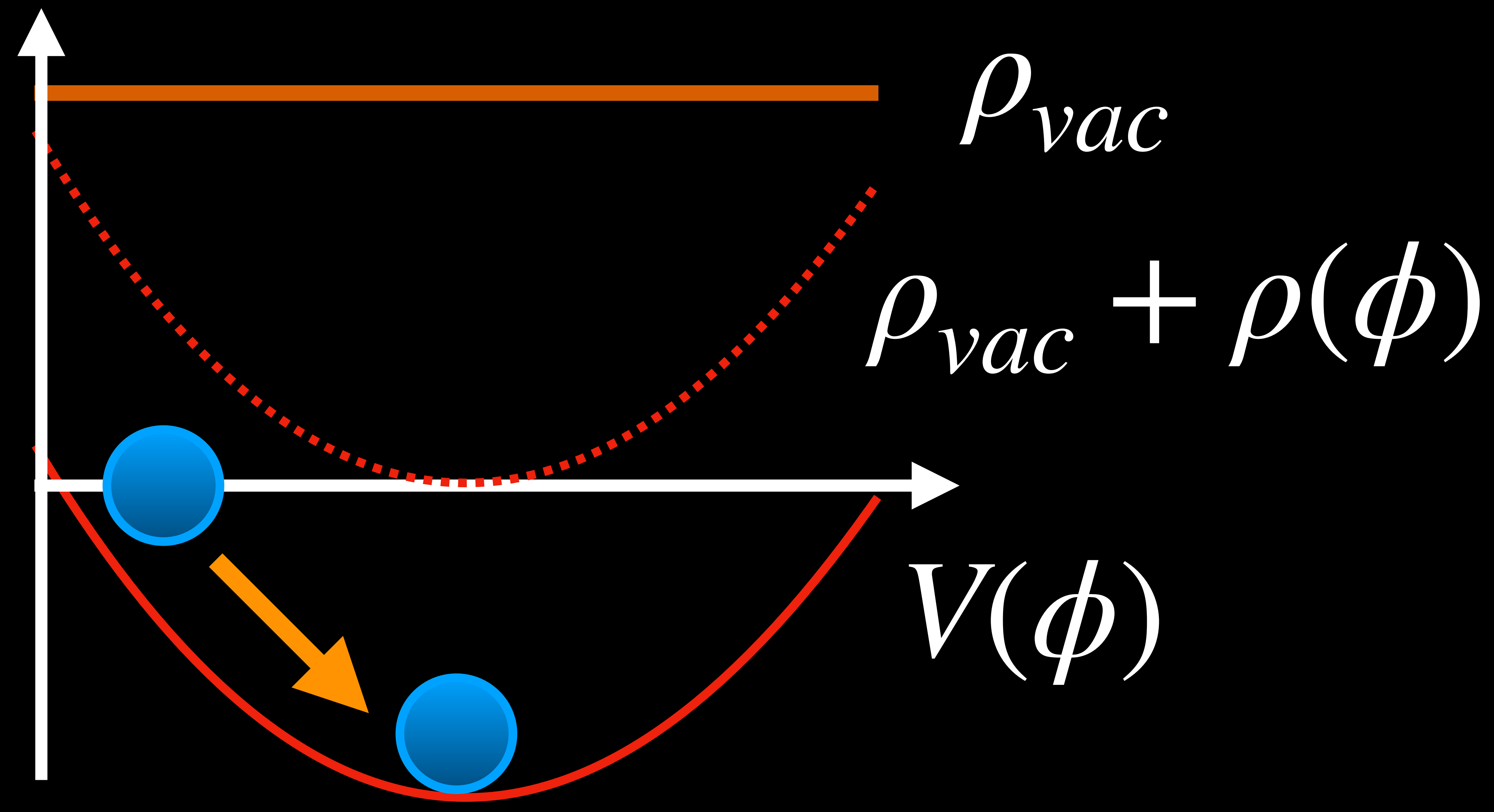
- A barrier is **Weinberg's No-Go Theorem (1989)**

The Cosmological Constant Problem

- **Weinberg's No-Go Theorem**
  - Not possible to relax to a static cancellation without fine tuning.

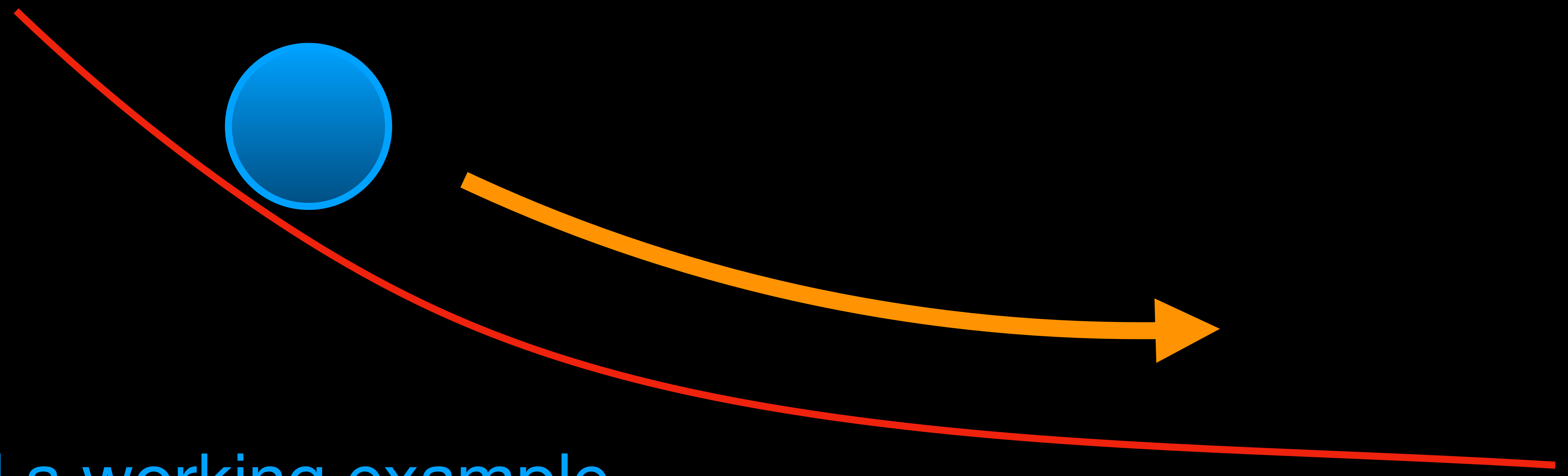
- A static solution will not account for vacuum instability
  - Needs constant cancellation.

- Cannot account for phase transitions.



A Self-Tuning Universe

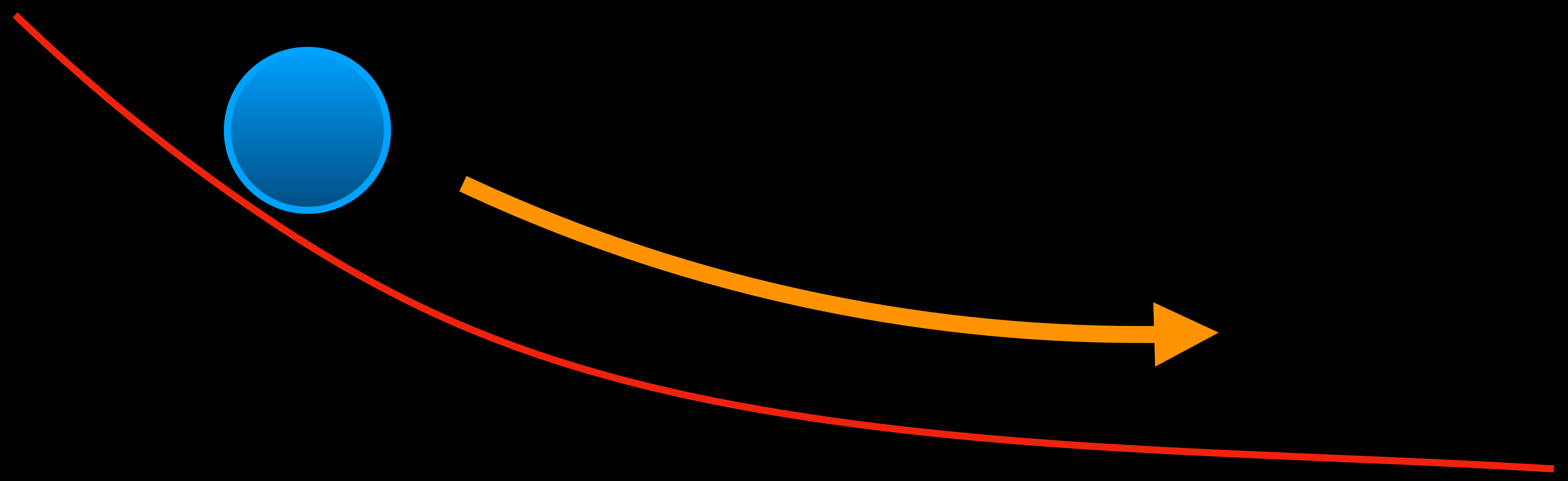
- But what about a dynamical solution?
- Charmousis et al (2012) & Copeland et al. (2012) found Horndeski theory does, in principle, permit a dynamical solution - Fab Four Theory.



- But could not find a working example
  - Tuned to Minkowski space, so no acceleration phase.
  - No matter-dominated phase.
- Measurement of c_T adds strong constraints on Modified Gravity sector.

A Self-Tuning Universe

- Appleby & Linder (2018) ‘Well-Tempered’ model looked promising.
- A de Sitter limit, so acceleration.
- Found models with matter-dominated regimes.



- Made strong mathematical assumptions - severely limits choices.
- Very complex model - mechanism unclear.

A Self-Tuning Universe

- Khan & ANT (2022) looked for simpler solutions.
- Start with models satisfying gravitational wave constraint and set $G_4 = M_{Pl}^2/2$

$$\mathscr{L} = \frac{M_{Pl}^2}{2}R + G(\phi, X)\,\Box\,\phi + K(\phi, X)$$

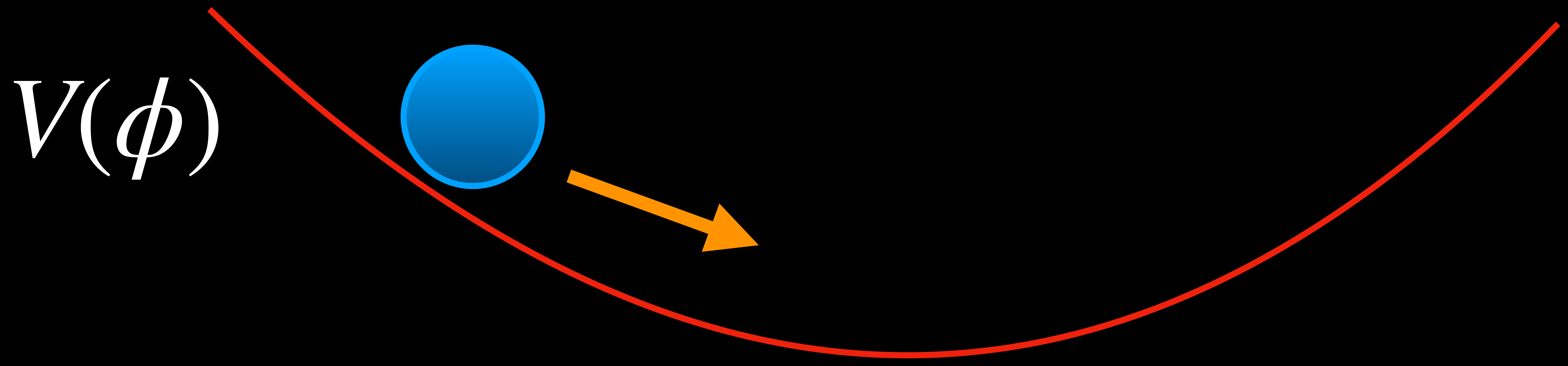
  - **Kinetic Gravity Braiding (KGB)** sector.

- Drop strong mathematical conditions, and use weaker, **physical**, constraints.
- Find model with accelerating attractor solutions, which can cancel a large cosmological constant term.

$$\mathscr{L} = \frac{M_{Pl}^2}{2}R + \frac{1}{M}\left(\sqrt{2X}\,\Box\,\phi - 3H_{dS}X\right) - V(\phi)$$

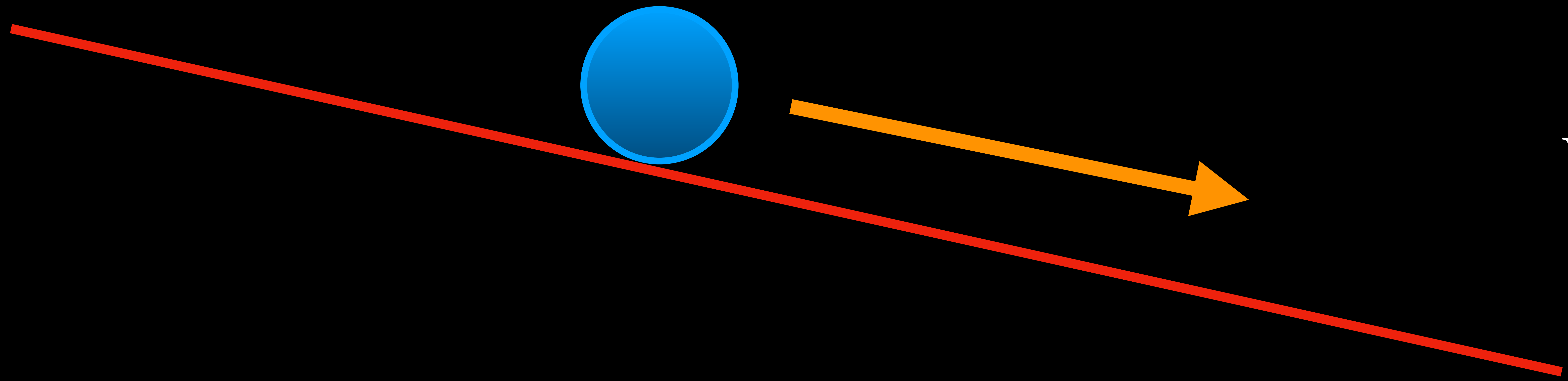
Scalar Field Dark Energy

- Let's remind ourselves of the basic scalar field model:
  - Energy-density: $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$
  - Field Equation: $\ddot{\phi} + 3H\dot{\phi} = -\frac{dV}{d\phi}$



Self-Tuning Universe

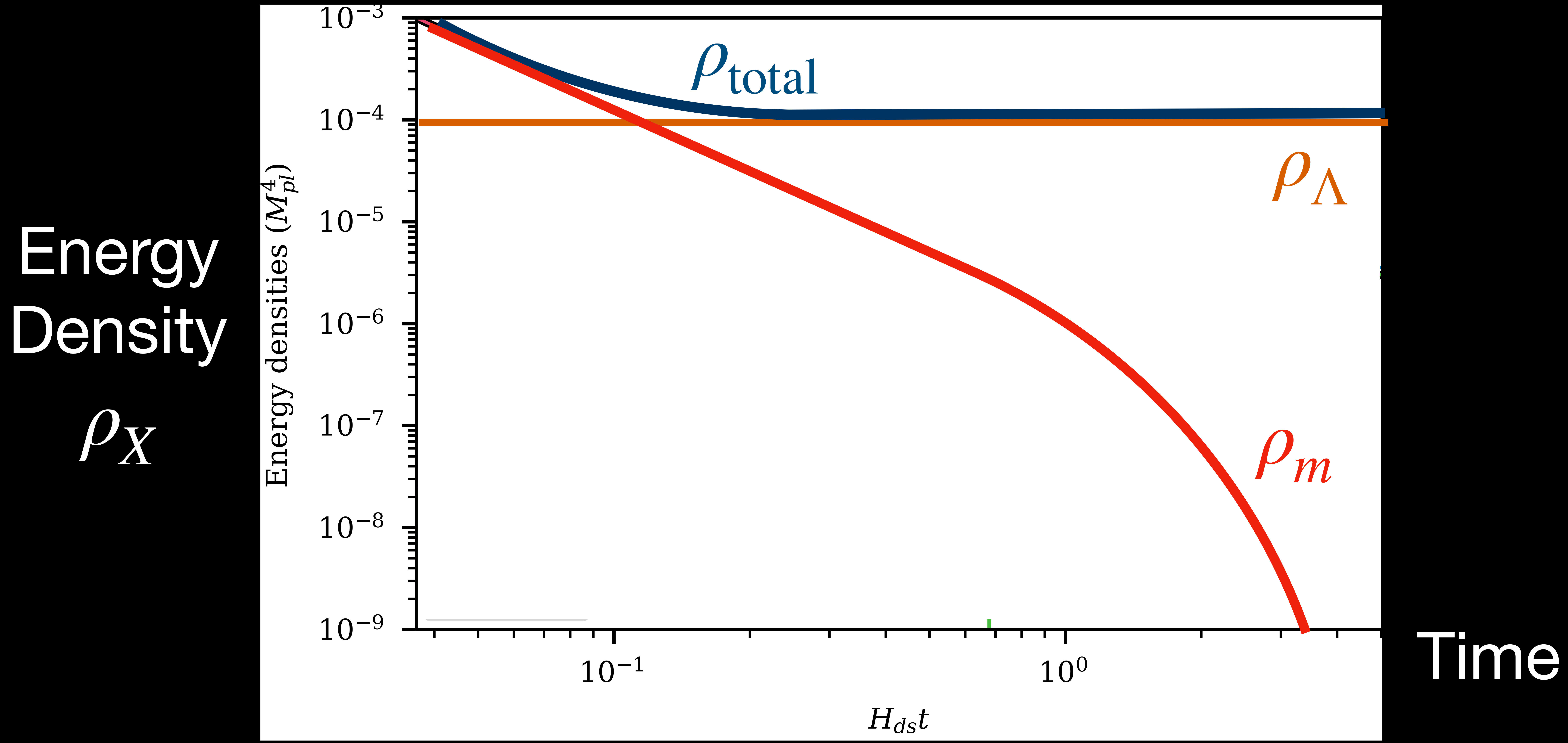
- Khan & ANT (2022) minimal self-tuning model in Horndeski Theory:
  - Energy-density: $$\rho_\phi = \frac{3}{2M}(2H - H_{dS})\dot{\phi}^2 + V(\phi)$$
  - Field Equation: $$(\ddot{\phi} + 3H\dot{\phi})(H - H_{\mathrm{dS}}) + \dot{H}\dot{\phi} = -\frac{dV}{d\phi}$$



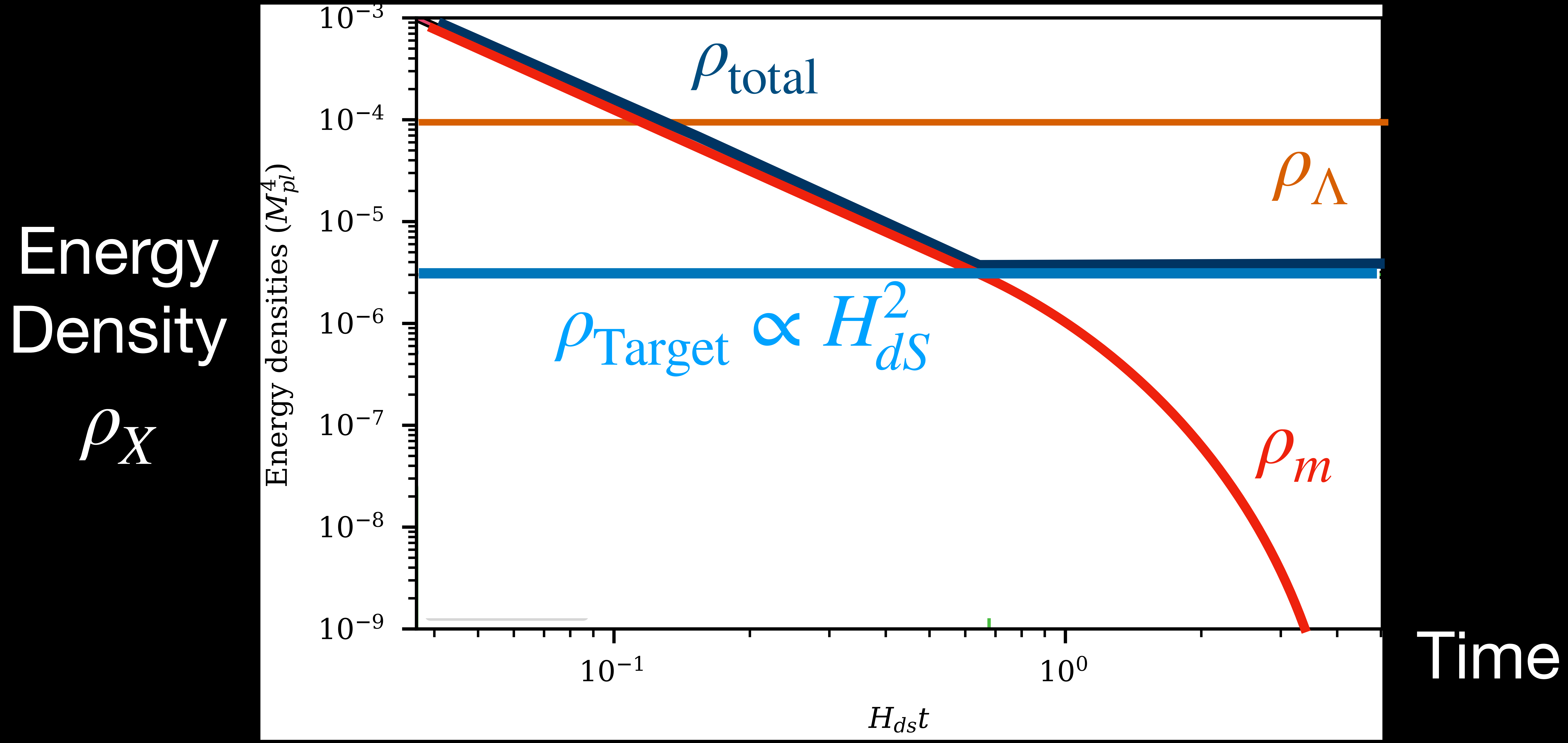
$$V(\phi) = -M^3\phi$$

- Linear potential ‘eats’ vacuum, modified kinetic term and field equation has accelerating attractor solution.

ΛCDM, No Self-Tuning



Add Self-Tuning Field



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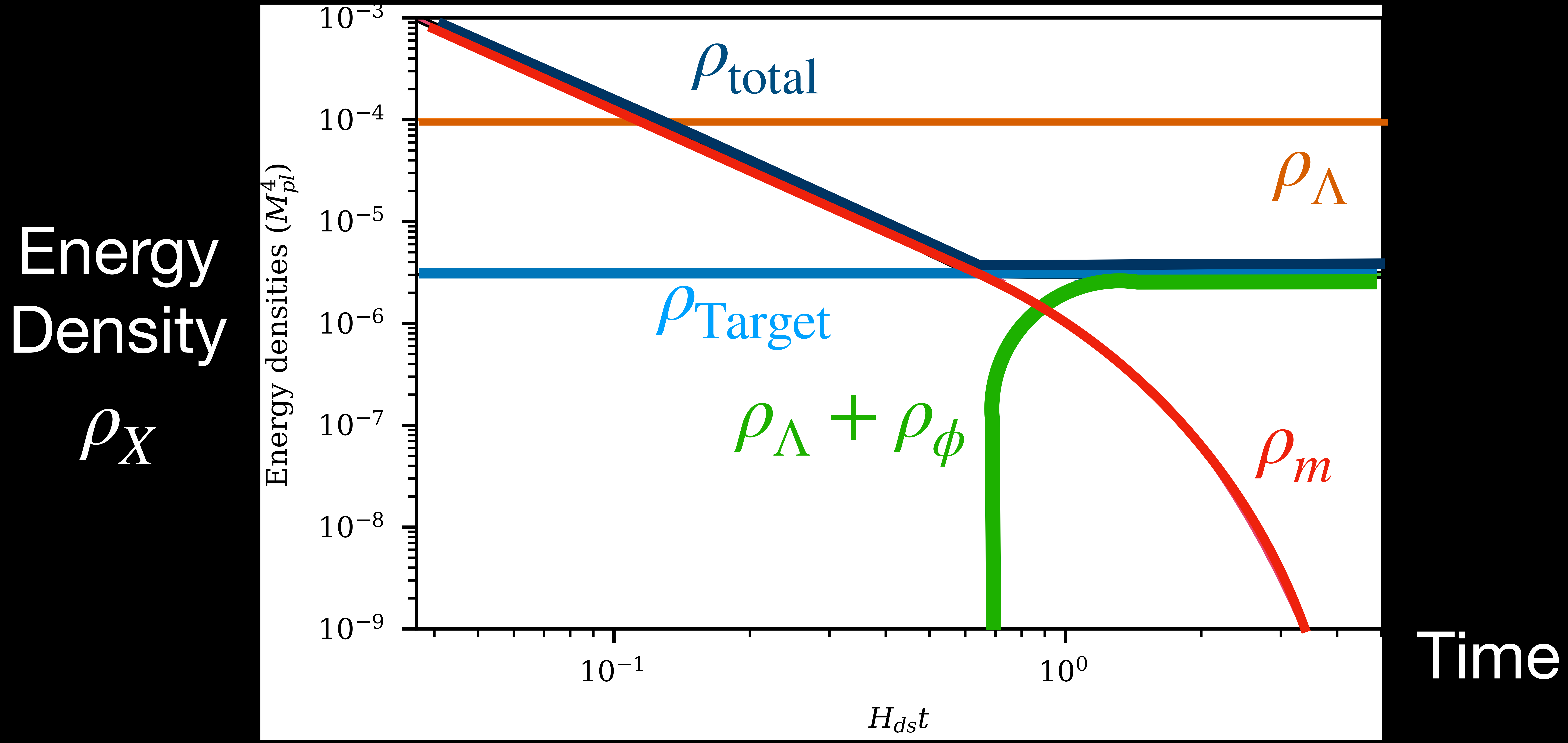
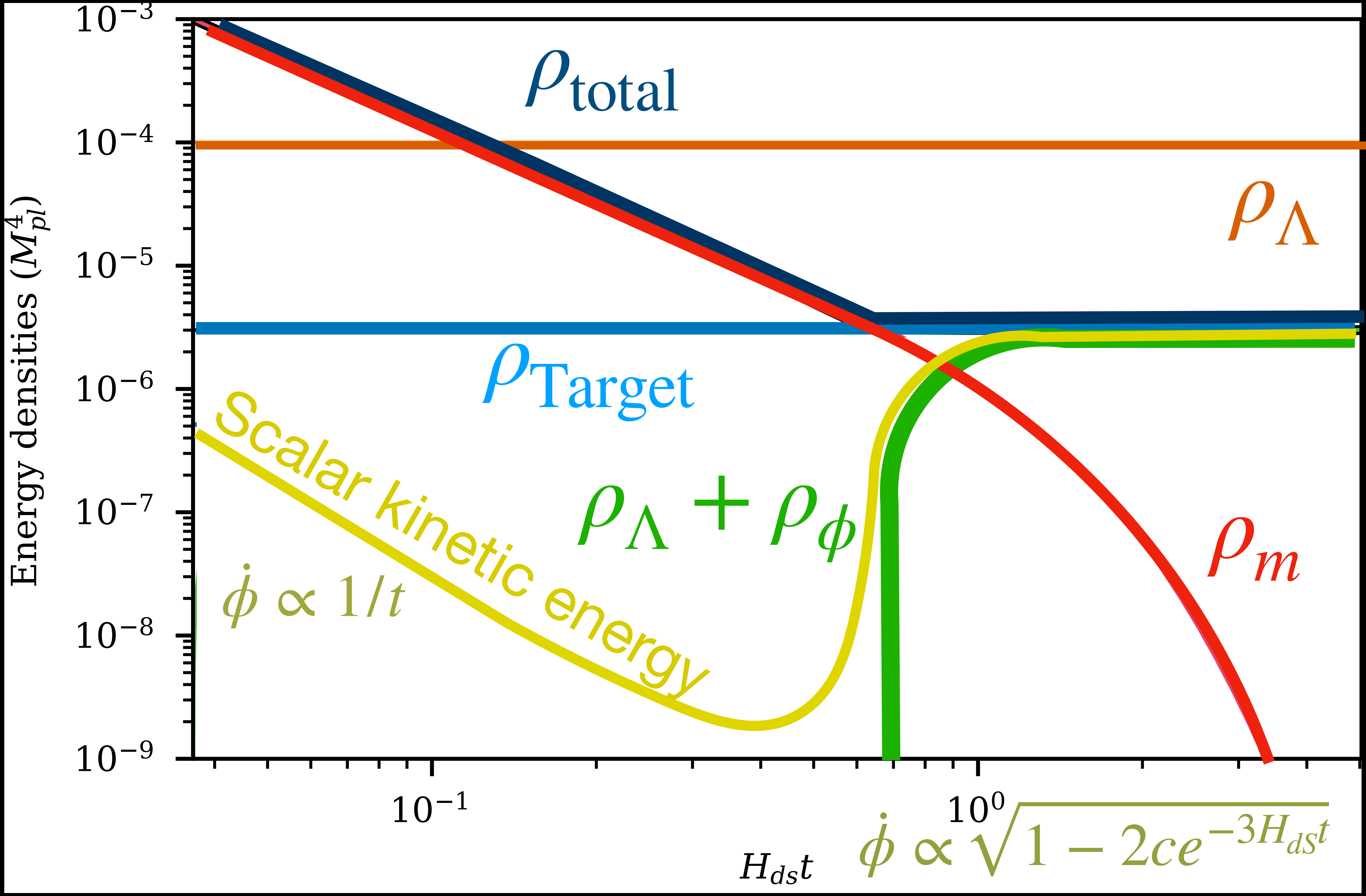


Add Self-Tuning Field

Energy Density

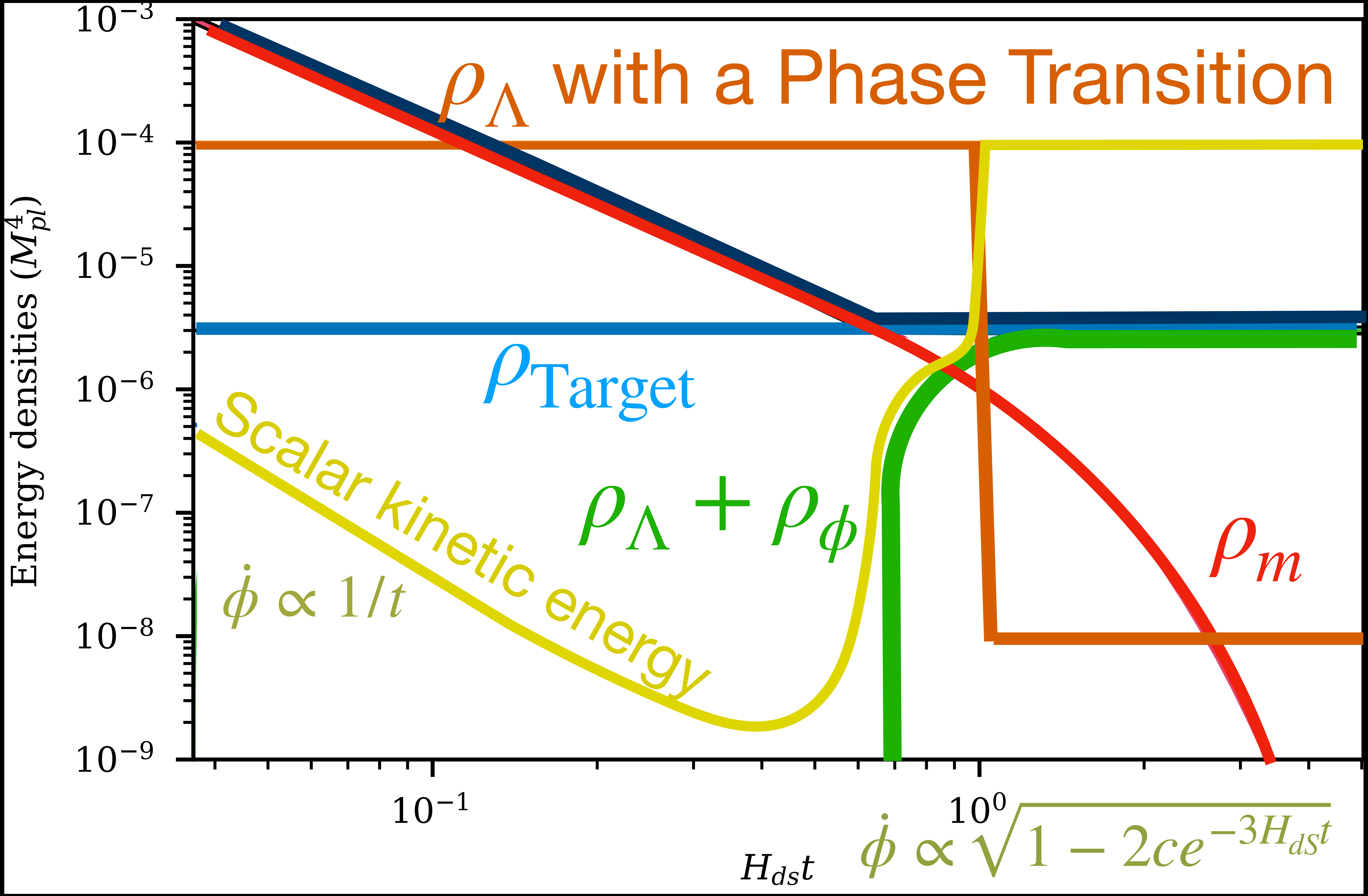
ρ_X



Time

With a Phase Transition

Energy Density ρ_X



Time

Energy Scales

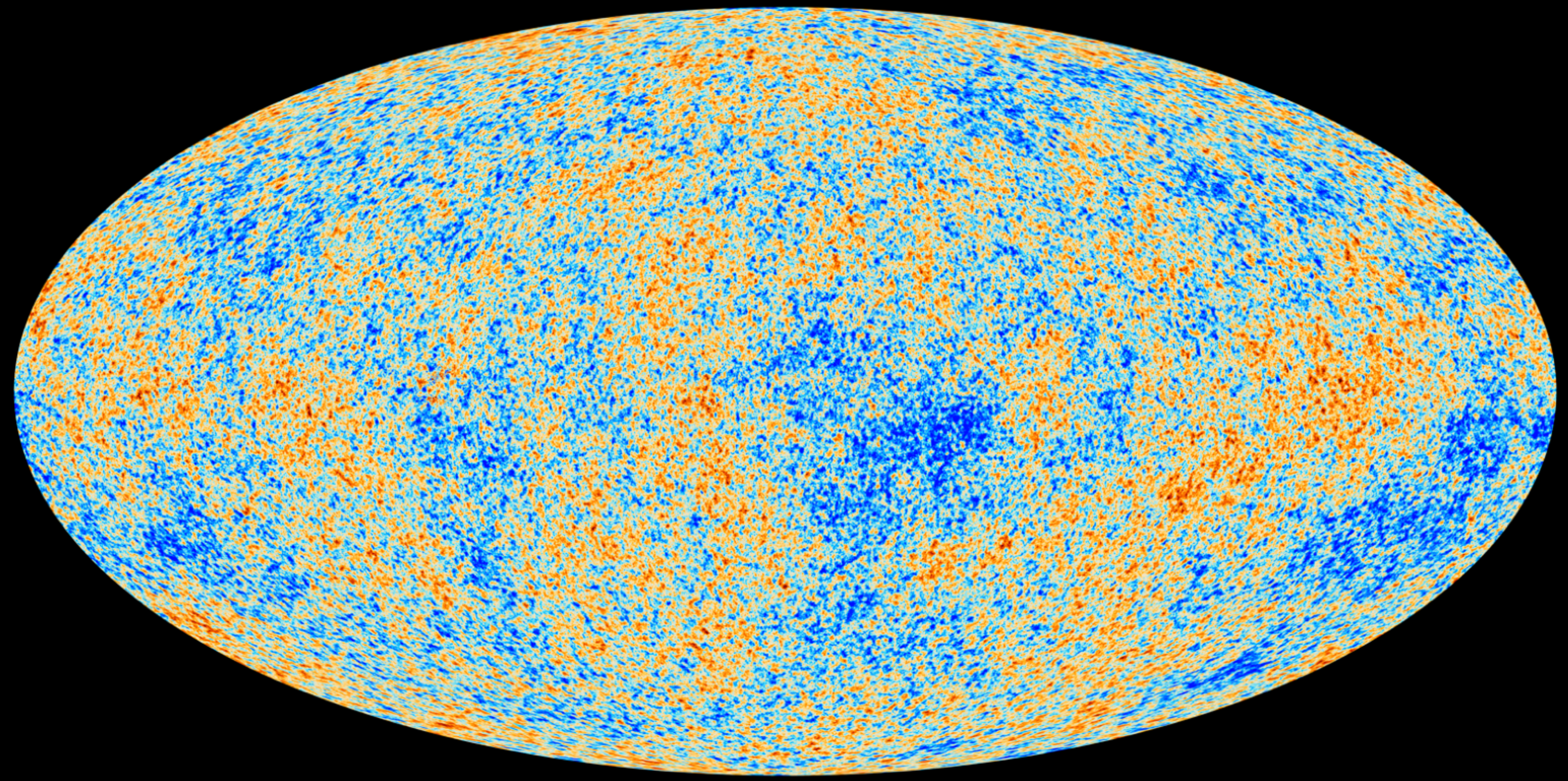
- To match observations the scalar field need an ultralight mass scale,

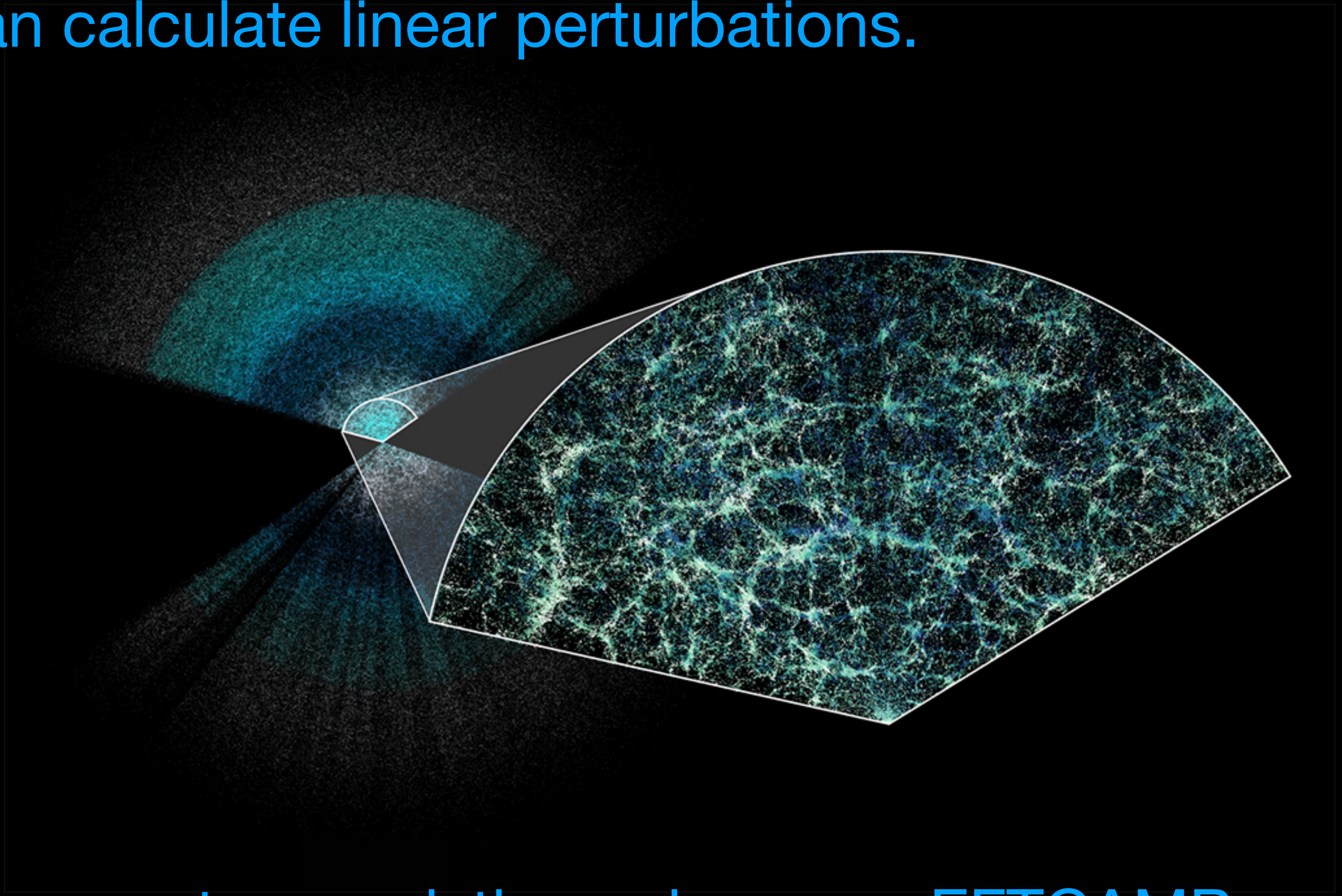
$$M \sim H_0 \sim 10^{-60} M_{Pl} \sim 10^{-33} eV$$

- And we set $H_{dS} = H_0$
- Large ϕ field values, but may be protected by ***Shift Symmetry*** $\phi \to \phi + c$.
- Quantum corrections are suppressed (Shift Symmetry and small $\dot{\phi}$).
- Satisfies Null Energy Condition, Laplace condition and is Ghost-free.
- Stable to initial conditions for attractor solution.
- Need slow-roll initial conditions to allow matter-domination, but wide range of values, $\dot{\phi}^2/2 < M^2 M_{Pl}^2$.

Structure Formation in MSTM

- The MSTM is simple enough we can calculate linear perturbations.



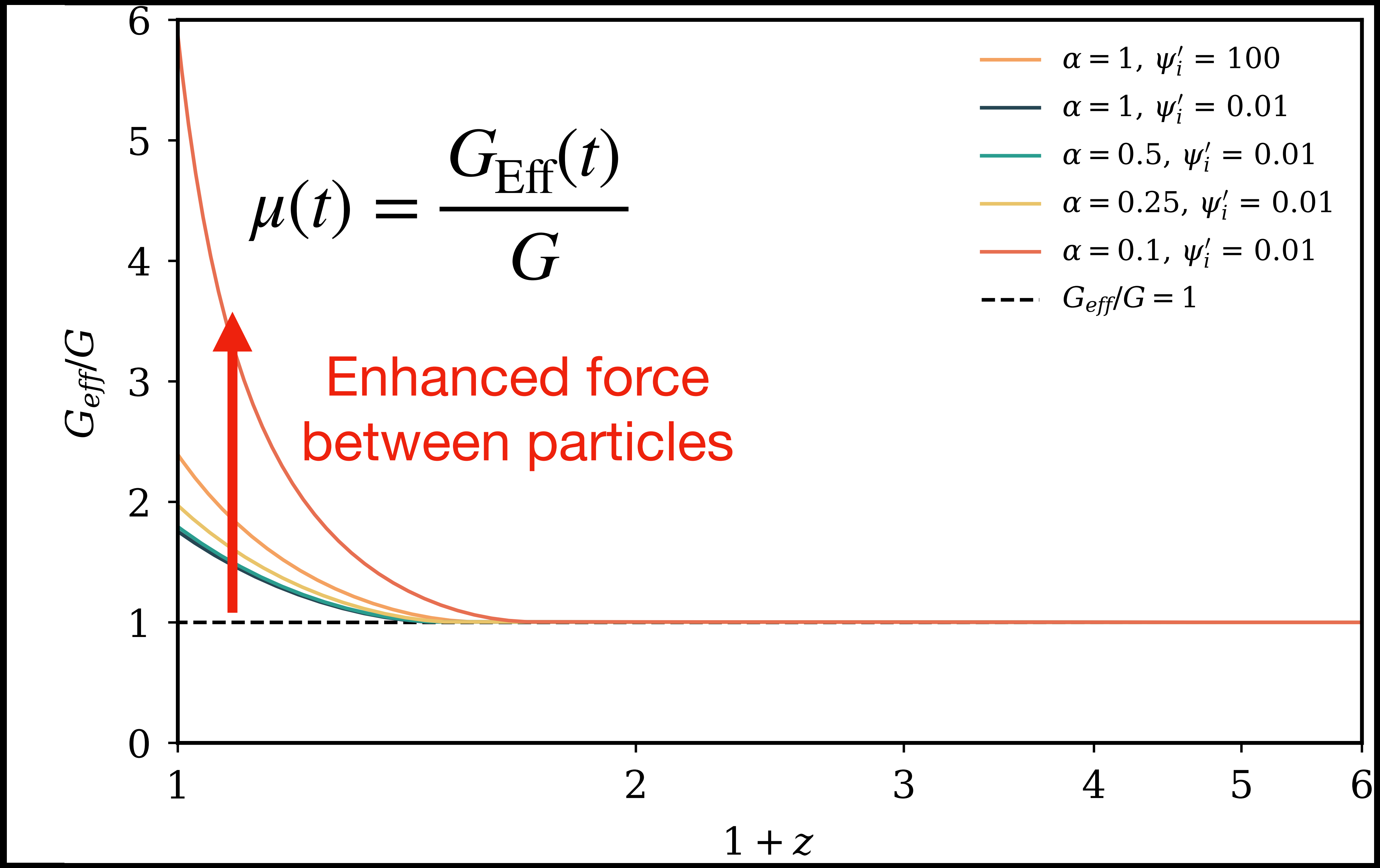


- As the background is not ΛCDM, cannot use existing solvers, eg EFTCAMB, Hi-CLASS.

Structure Formation in MSTM

- In the Quasi-Static Approximation $kc_s \gg aH$, and $\dot{X} \leq HX$, yields modified evolution of overdensities, $\delta = (\rho_m - \langle\rho_m\rangle)/\langle\rho_m\rangle$,

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi\mu(t)G\rho_m\delta$$



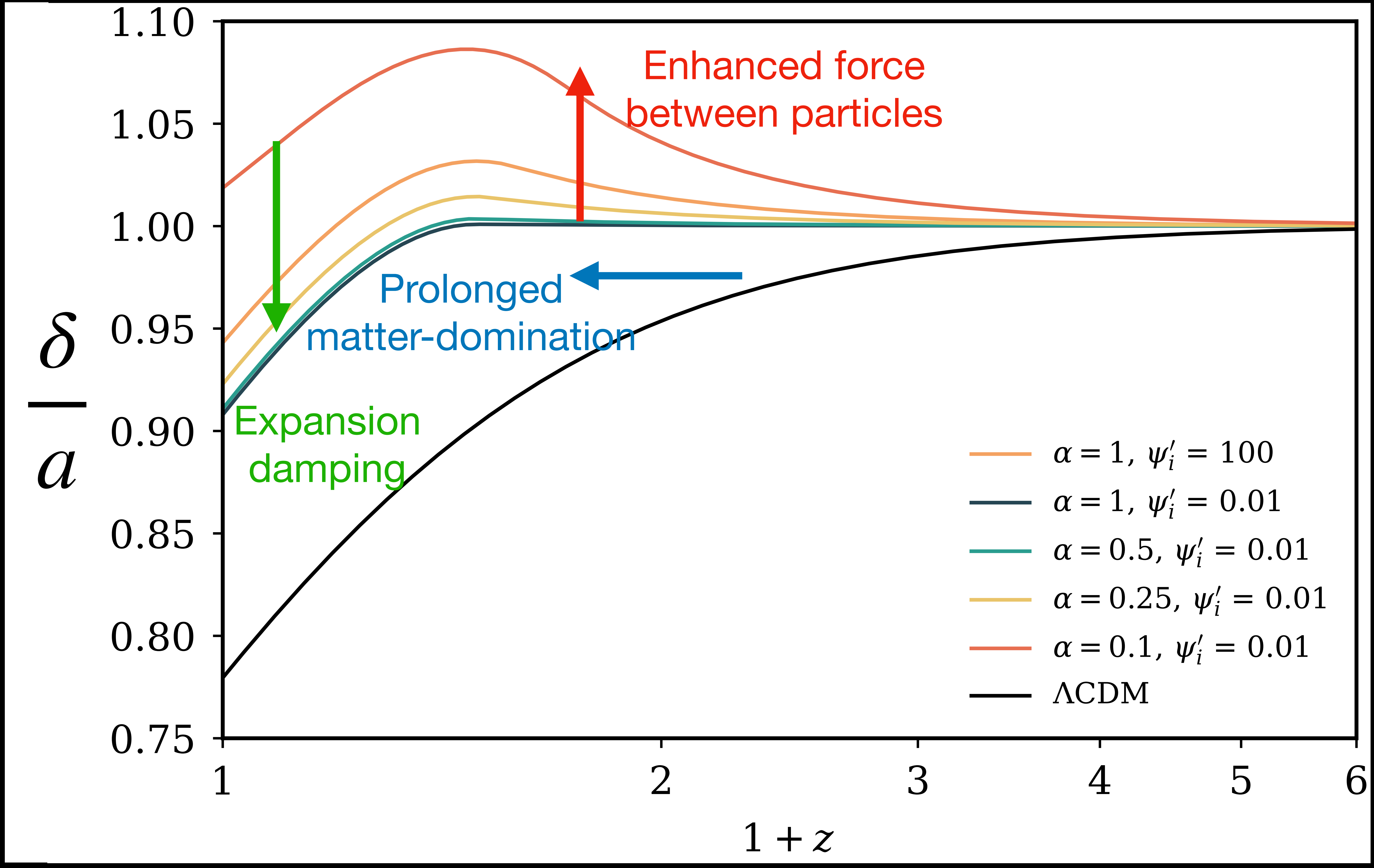
- Scalar field induces extra forces between particles

$$\mu(t) = \frac{G_{\rm Eff}}{G} = 1 + \frac{c_0 M\dot{\phi}^2}{2M_{Pl}^2(M\ddot{\phi}/\dot{\phi} + 4H - 3H_{dS}) - c_0 M\dot{\phi}^2}$$

Structure Formation in MSTM

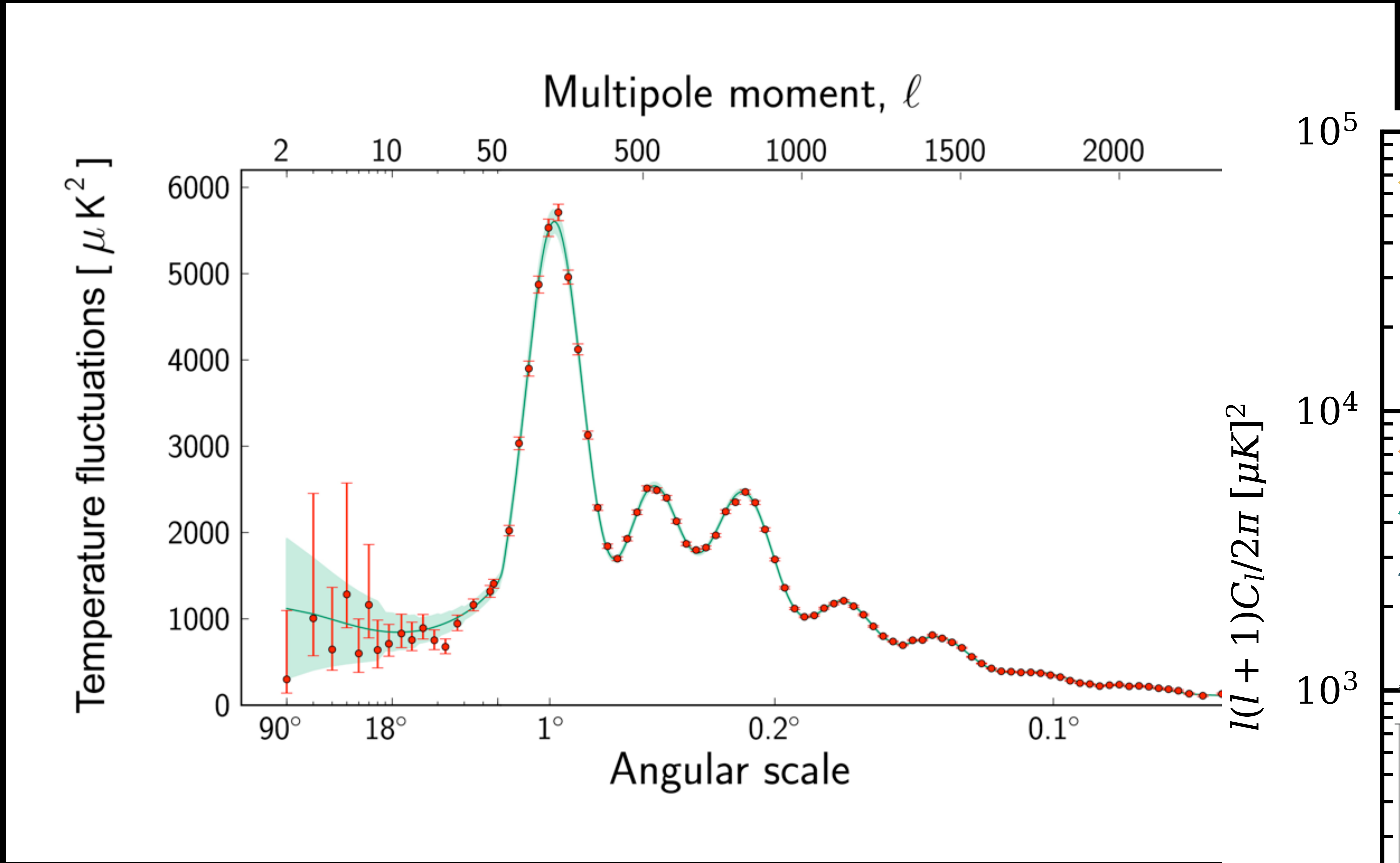
- The MSTM is simple enough we can calculate evolution of linear perturbations.
- Evolution of linear overdensities,

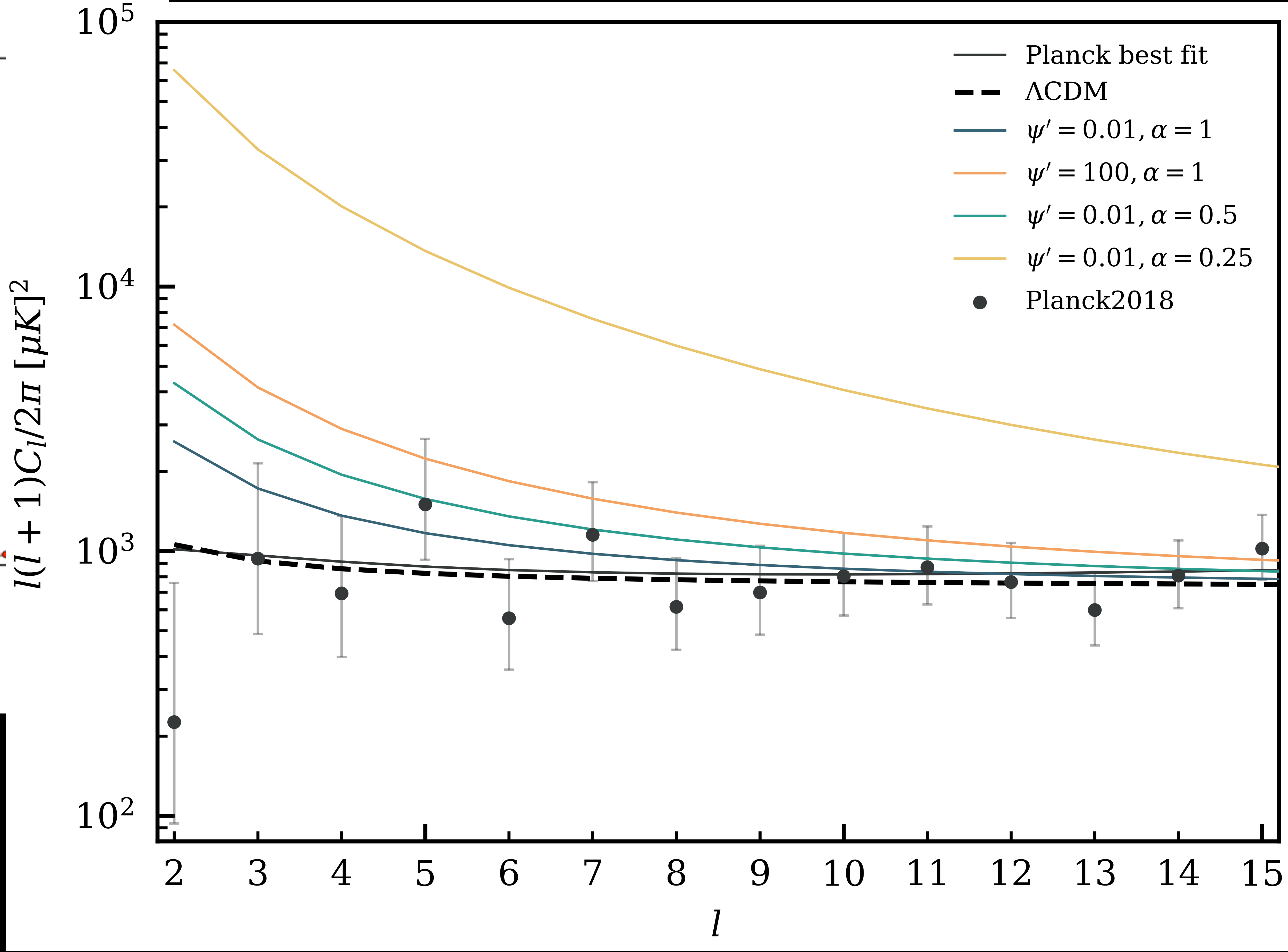
$$\delta = \frac{\rho - \langle\rho\rangle}{\langle\rho\rangle}$$



Structure Formation in MSTM

- Integrated Sachs-Wolfe (ISW) Effect - decay of dark matter potentials





- So model tends to enhance ISW.

Structure Formation in MSTM

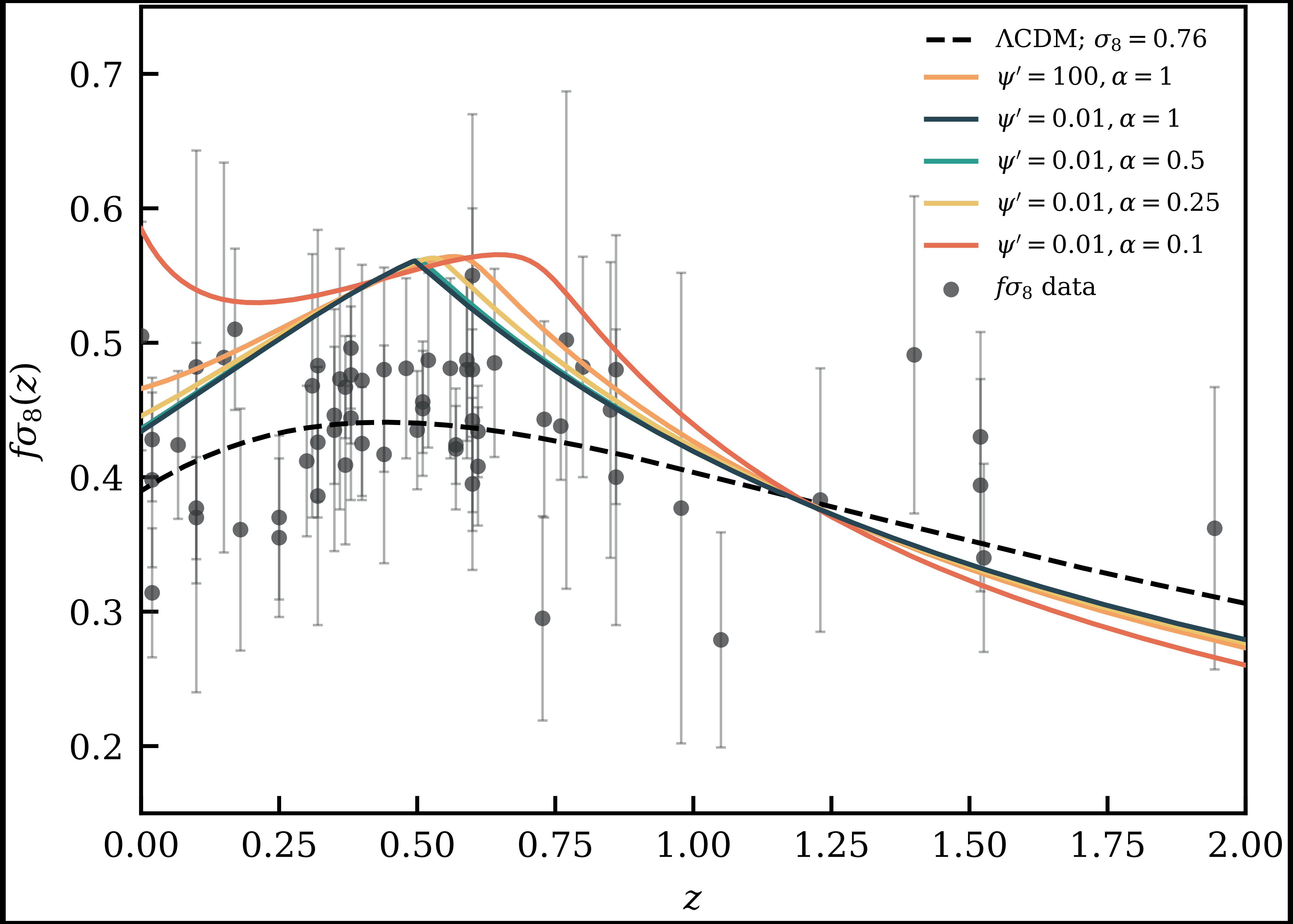
- Growth rate of structure and clustering amplitude, $f\sigma_8(z)$:

- Growth rate

$$f = \frac{d\ln\delta}{d\ln a}$$

- Clustering variance:

$$\sigma_8^2(z) = \langle \delta^2(R = 8h^{-1}\mathrm{Mpc}, z)\rangle$$



- Model slightly too high.

Closing Comments

- A **simple, physical mechanism** can solve the (Old) **Cosmological Constant Problem.**
- **Dynamical scalar field** avoid’s Weinberg’s **No-Go Theorem.**

- Allows for **matter-domination** and **acceleration** phases.
- **Avoids fine-tuning** initial conditions (wide range, but requires slow-roll).

- **Enhanced forces** for structure formation possibly a problem for this model.
- Investigating ways to **alleviate** this in the wider model space.

- **Euclid data will soon provide strong constrains on all DE/MG models.**

End