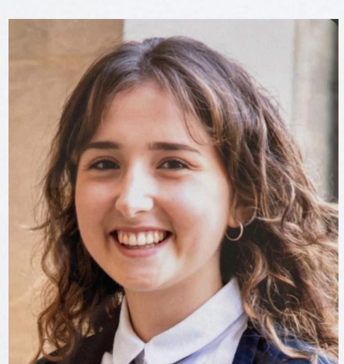
STRING THEORY AND THE FIRST HALF OF THE UNIVERSE

Joseph Conlon

Planck 2025
Padua

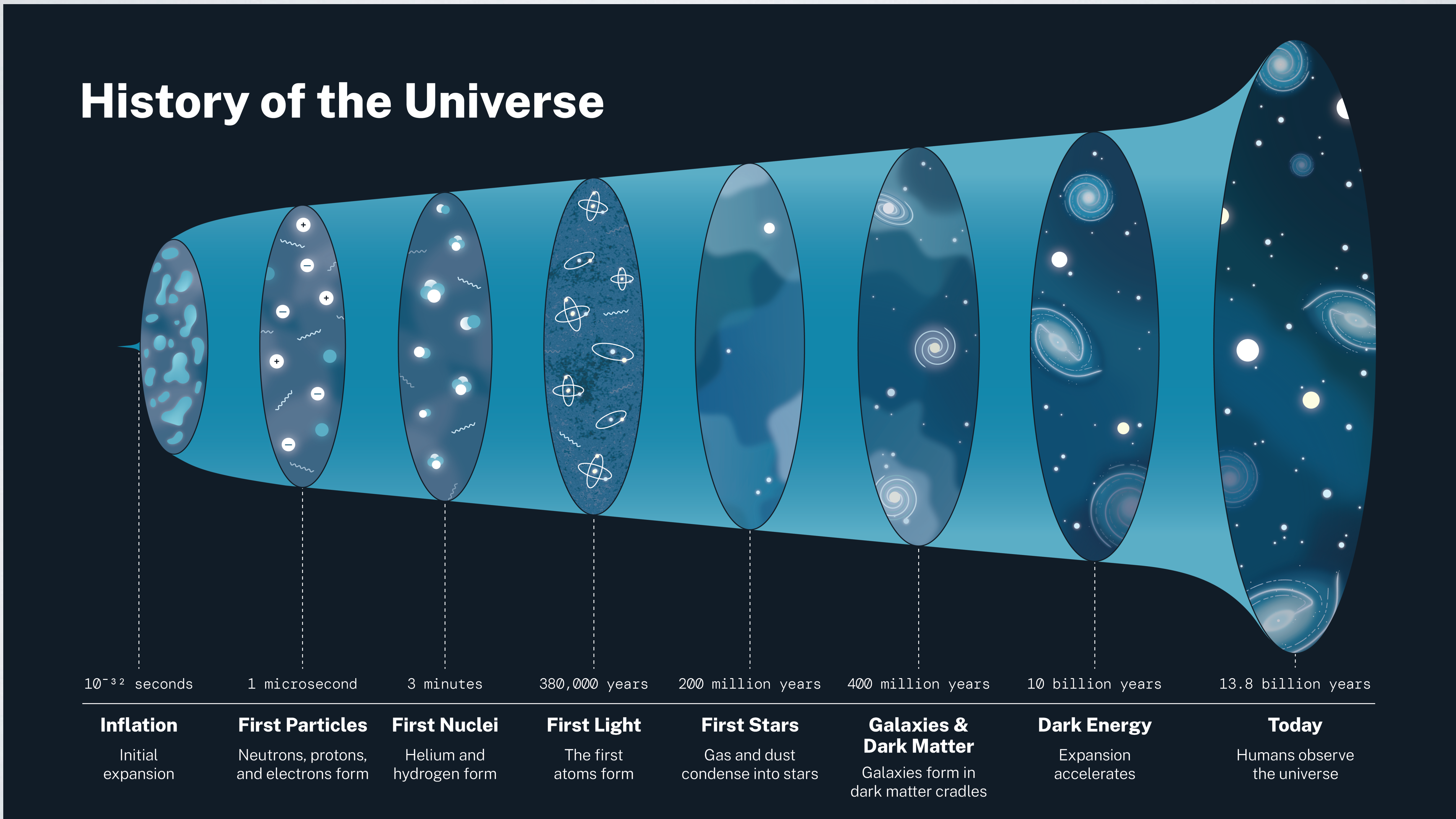
Sanchez-Gonzales, JC, Copeland, Hardy, 2505.14187,
JC, Copeland, Hardy, Sanchez-Gonzales 2406.12637,
also see Apers, JC, Copeland, Mosny, Revello 2401.04064)

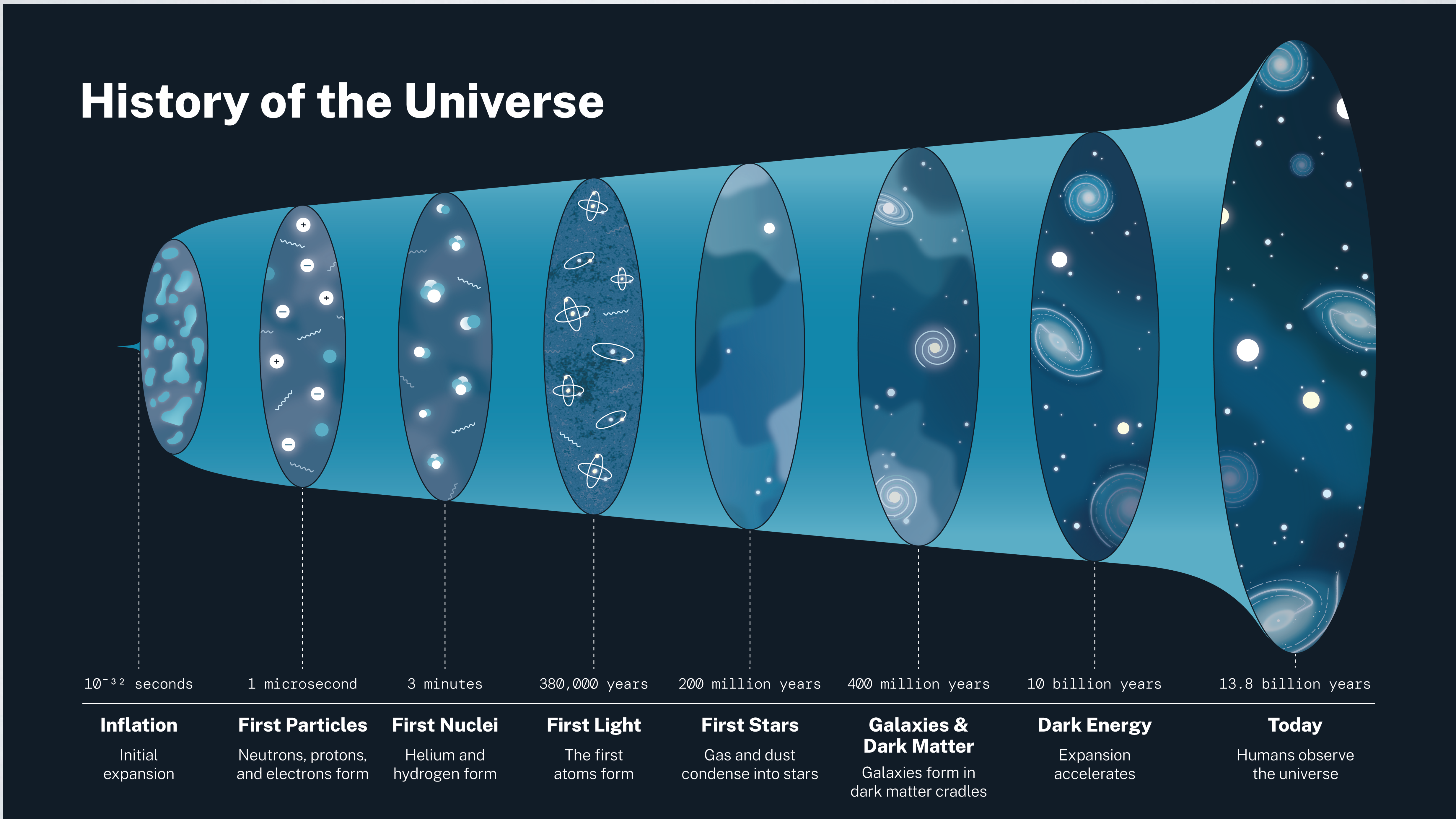
Cf Brunelli parallel talk

1. THE FIRST HALF OF THE UNIVERSE

THE KNOWN HISTORY OF THE UNIVERSE

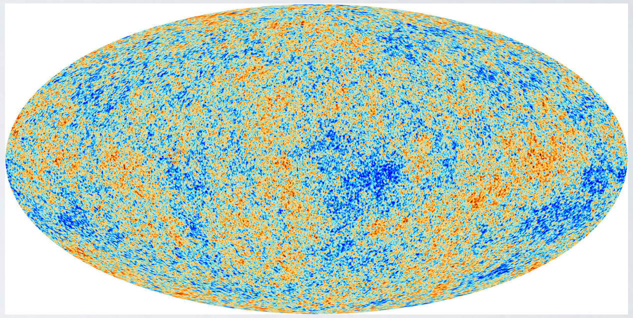


THE ~~KNOWN~~ HISTORY OF THE UNIVERSE



THE ~~KNOWN~~ HISTORY OF THE UNIVERSE

- State of universe during inflation (10^-30s? Depending on scale of inflation) is **constrained** by structure of the CMB



- State of universe during nucleosynthesis (10^{-2}s to $\mathcal{O}(100)$s) is **constrained** by primordial element abundances

- *Minimal* constraints exist between these two epochs; up to thirty orders of magnitude in time and **half the lifetime of the universe on a logarithmic scale**

II. STRING THEORY, PHENOMENOLOGY AND COSMOLOGY

STRING THEORY: THE CASE FOR THE PROSECUTION

String theory claims to be a theory of *quantum gravity*, relevant for physics near the Planck scale

$$M_P \simeq 2.4 \times 10^{18}\,\mathrm{GeV}.$$

Inflation occurs at $\Lambda_{inf} \lesssim 10^{16}\,\mathrm{GeV}$ and all other subsequent physics scales are even smaller.

For physicists interested in `ordinary' sub-Planckian physics, why care about string theory?

STRING THEORY: THE CASE FOR THE PROSECUTION

If $\Lambda_{\text{everything else}} < M_P$, what can string theory offer that is not already provided by

- Low-energy effective quantum field theory
- The Standard Model and Beyond-the-Standard-Model particle physics (susy, axions, WISPs, etc etc)
- The Standard Cosmology and extensions (dark radiation, quintessence etc)

WHAT STRING THEORY OFFERS

Theories of quantum gravity allow Planck-scale computation and so give control over Planck-suppressed operators (cf Fermi theory and electroweak theory)

- Control of Planck-suppressed operators implies that in an expansion

$$\mathscr{L}(\phi) \to \mathscr{L}(\phi)\left(1 + \frac{\alpha\phi}{M_P} + \frac{\beta\phi^2}{M_P^2} + \frac{\gamma\phi^3}{M_P^3} + \dots\right)$$

  we are able to determine the coefficients α, β and γ.

- Such operators need Planck-scale theories; cannot determine them just from low-energy EFT.

- When do they matter?

WHEN DOES STRING THEORY MATTER?

When does control over Planck-suppressed operators matter?

- Long-lived particles (e.g. moduli) with only gravitational-strength interactions

  Their decay rate is $\Gamma_\Phi \sim \frac{1}{8\pi}\frac{m_\Phi^3}{M_P^2}$ and they can dominate the energy density of the early universe (moduli problem).

- η problem of inflation: how to control contributions to potential of form.
  $\delta V(\phi) = \frac{\phi^2}{M_P^2} V(\phi)$ which can destroy flatness of inflationary potential

- Transplanckian field excursions $\Delta\phi \geq M_P$ in field space.

TRANSPLANCKIAN FIELD EXCURSIONS AND COSMOLOGY

Much of cosmology involves scalar fields Φ_i coupled to general relativity (inflation / quintessence / dynamical dark energy). Which epochs of the universe involve transPlanckian field excursions?

- Large-field inflation models (e.g. chaotic inflation) resulting in large CMB tensor B modes)
- Extended epochs where scalar field kinetic energy $\dot{\Phi}^2$ is a large contribution to universe energy density: occurs through either kination or tracker epochs

KINATION

- During roll, with universe in kination epoch, field evolves as

$$\Phi(t) = \Phi_0 + \sqrt{\frac{2}{3}} M_P \ln\left(\frac{t}{t_0}\right)$$

- Field moves through $\sim M_P$ in field space each Hubble time

  Extended kination epoch implies large transPlanckian field excursions

- String theorists should **care!** - any extended kination epoch requires trans-Planckian field excursions $\Delta\Phi \gg M_P$.

- Cosmologists should **care!** - any extended kination epoch requires theory of the Planck scale to control it.

- Relatively little work on understanding kination epochs in string theory

TRACKER EPOCHS

- A rolling scalar field on an exponential potential $V = V_0 e^{-\lambda \Phi}$ in a radiation background reaches a tracker solution in which field evolves as

$$\Phi(t) = \Phi_0 + \frac{2M_P}{\lambda} \ln\left(\frac{t}{t_0}\right)$$

- Field motion is *slightly* slower than for kination but field still moves through $\sim M_P$ in field space each Hubble time

  Extended tracker epoch implies large transPlanckian field excursions

- String theorists should **care!** - any extended tracker epoch requires trans-Planckian field excursions $\Delta\Phi \gg M_P$

- Cosmologists should **care!** - any extended tracker epoch requires theory of the Planck scale to control it

III. THE EDGE OF THE WORLD

STRING THEORY: CENTRE OF THE WORLD?

- N=0 supersymmetry
  Hierarchies
  Weak couplings

Strong coupling

$$AdS_5 \times S^5$$

M-theory

$$g_s \sim 1, \mathrm{Volume} \sim \mathrm{l}_\mathrm{s}^6$$

Black hole entropy

Dualities

$$\mathcal{N} \geq 2 \text{ Supersymmetry}$$

Landau-Ginzburg models

The Map of
String Theory?

WHERE IS THE CENTRE OF THE WORLD?

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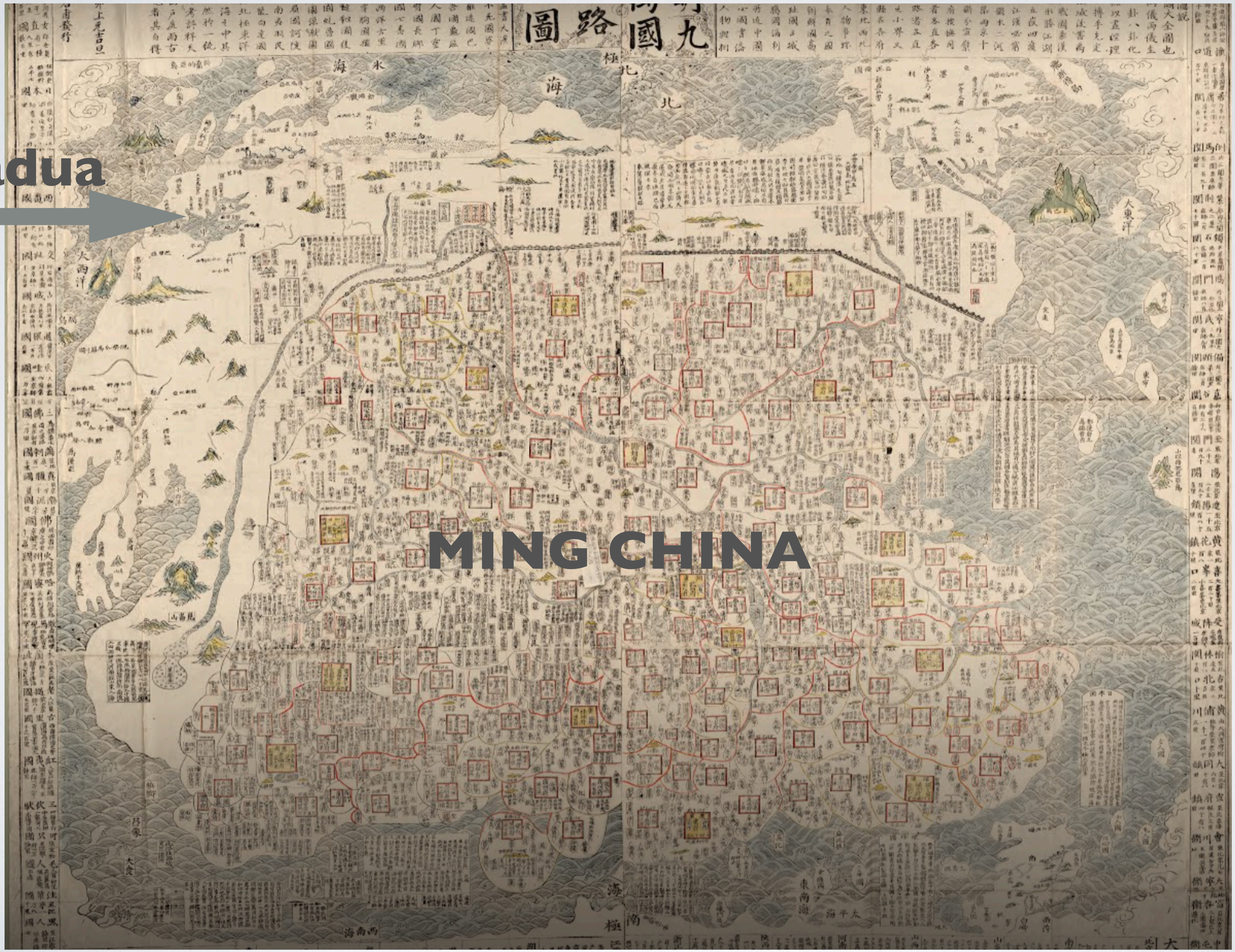

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Landau-Ginzburg models

The Map of
String Theory?

OUR HOME, THE UNIVERSE

- Our universe is *filled* with hierarchies and small numbers

$$\frac{\Lambda_{EW}}{M_P} \sim 10^{-16}$$

$$\frac{\delta\rho_{CMB}}{\rho} \sim 10^{-5}$$

$$\Lambda_{cc} \sim 10^{-120} M_P^4$$

$$\alpha_{SU(3)} \sim \frac{1}{11}, \alpha_{SU(2)} \sim \frac{1}{30}, \alpha_{U(1)_Y} \sim \frac{1}{60}$$

$$y_e \sim 10^{-5}, y_\mu \sim 10^{-3}, y_\tau \sim 10^{-2}$$

$$m_\nu \sim 10^{-3}\mathrm{eV}$$

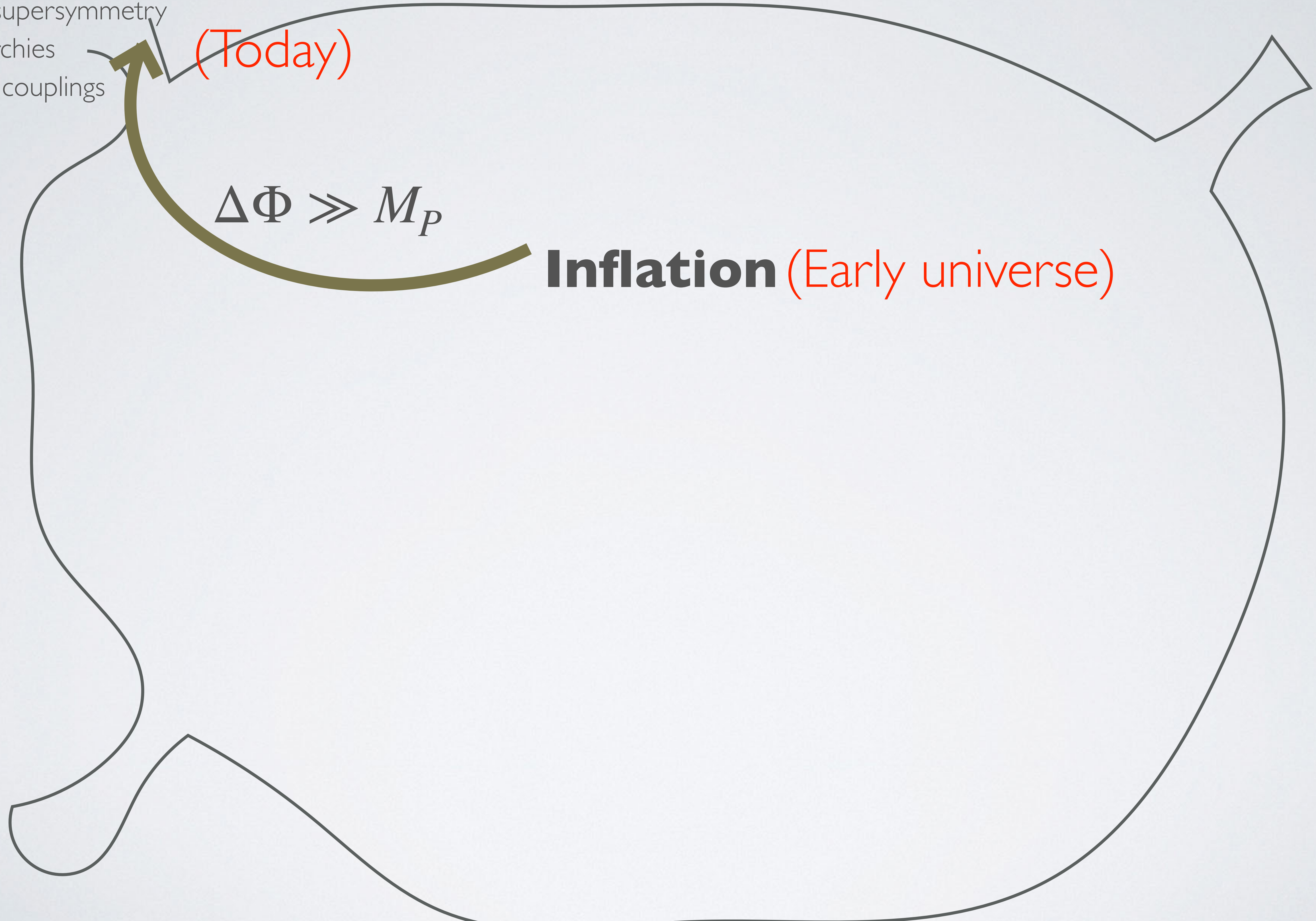
$$\theta_{QCD} \lesssim 10^{-10}$$

OUR HOME, THE UNIVERSE

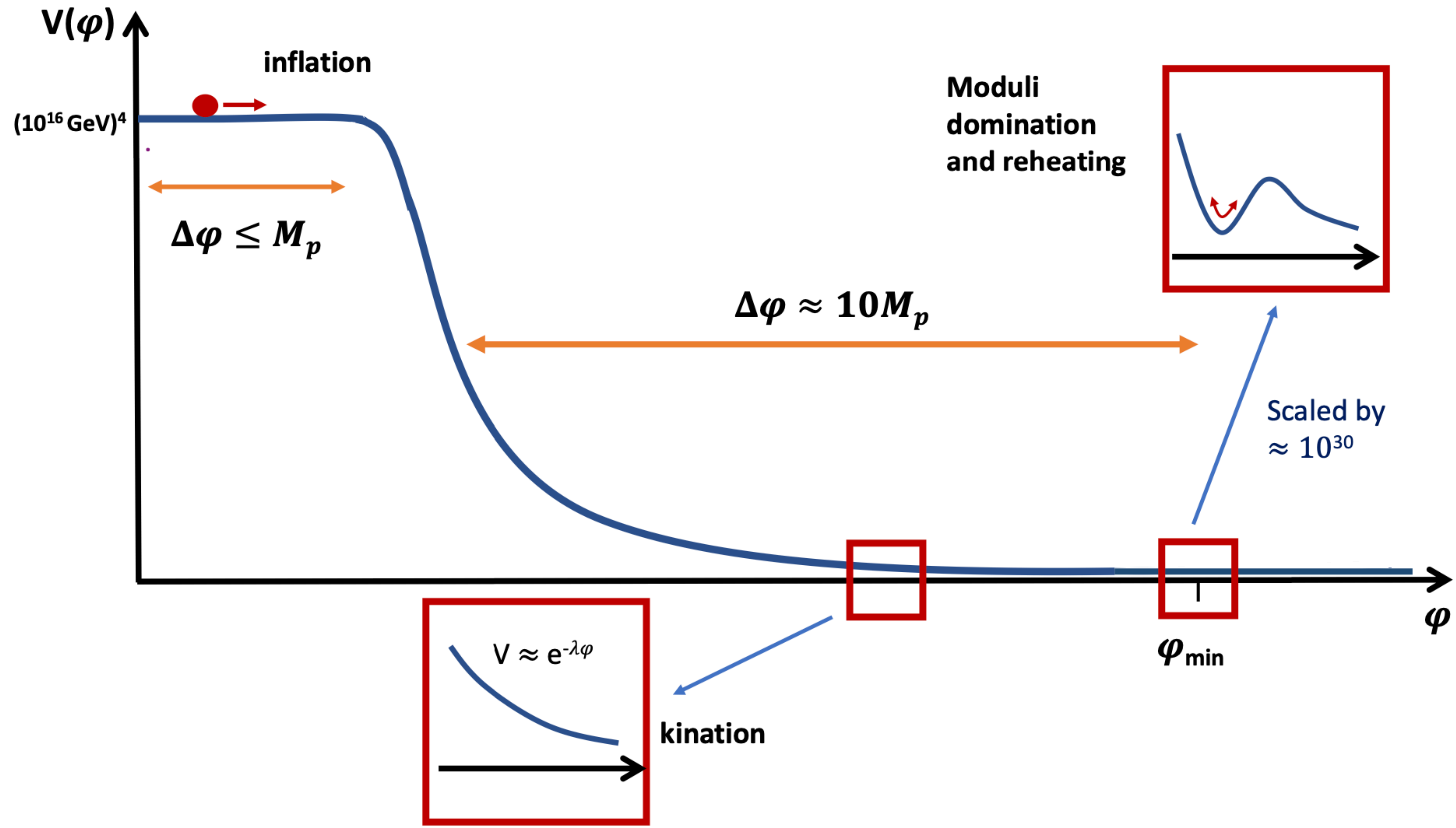
- The true string vacuum is the vacuum of *this* universe
- It must contain a method to generate hierarchies, small couplings and small numbers
- This makes the asymptotic boundaries of moduli space appealing

FROM CENTRE TO END OF THE WORLD

- N=0 supersymmetry
  Hierarchies
  Weak couplings

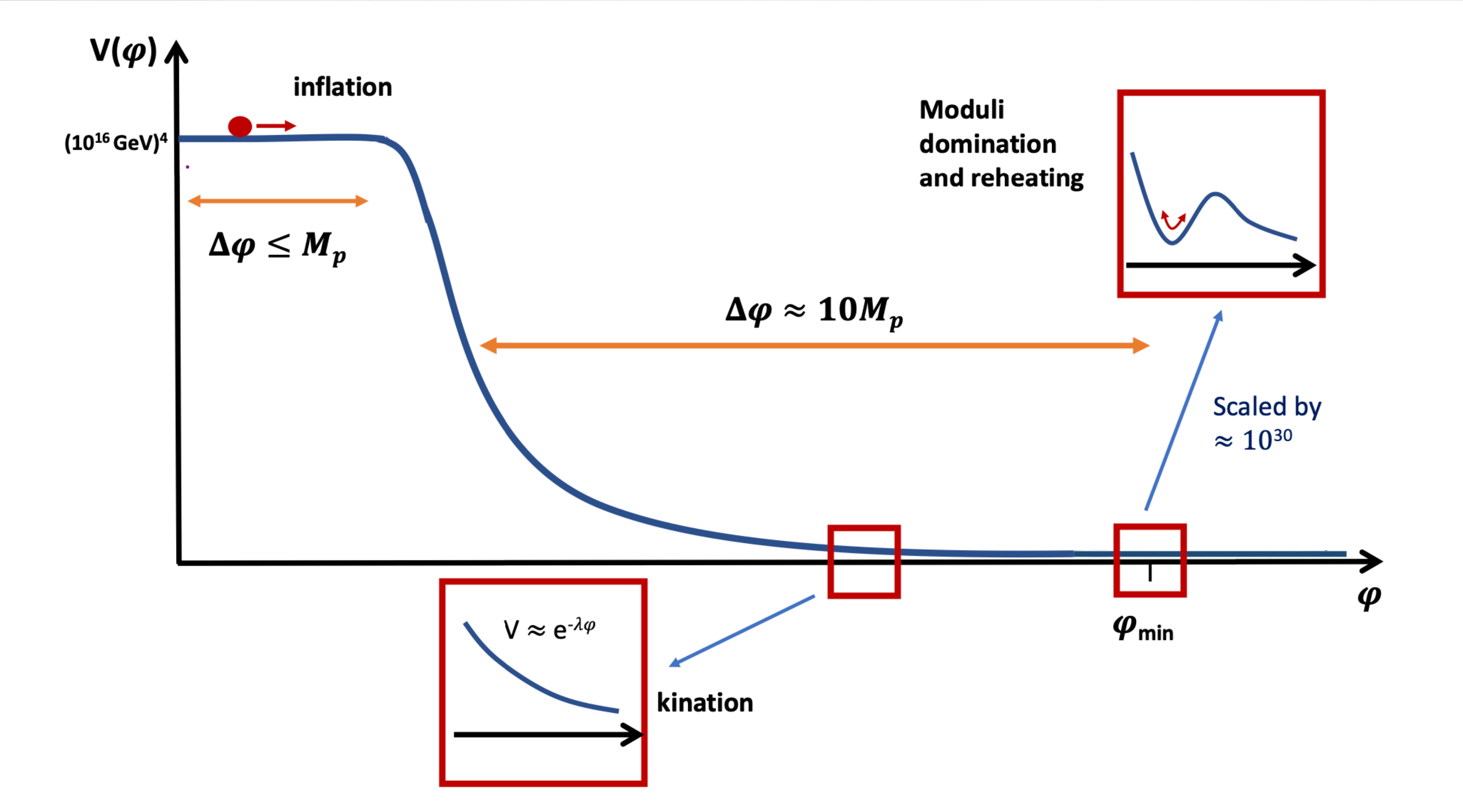


GETTING TO THE END OF THE WORLD

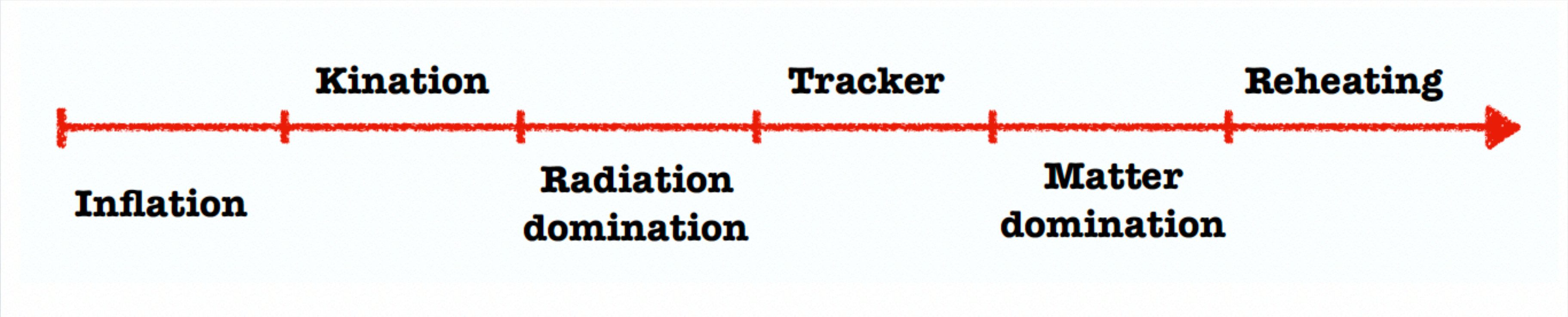


From review 2303.04819 Cicoli, JC, Maharana, Parameswaran, Quevedo, Zavala

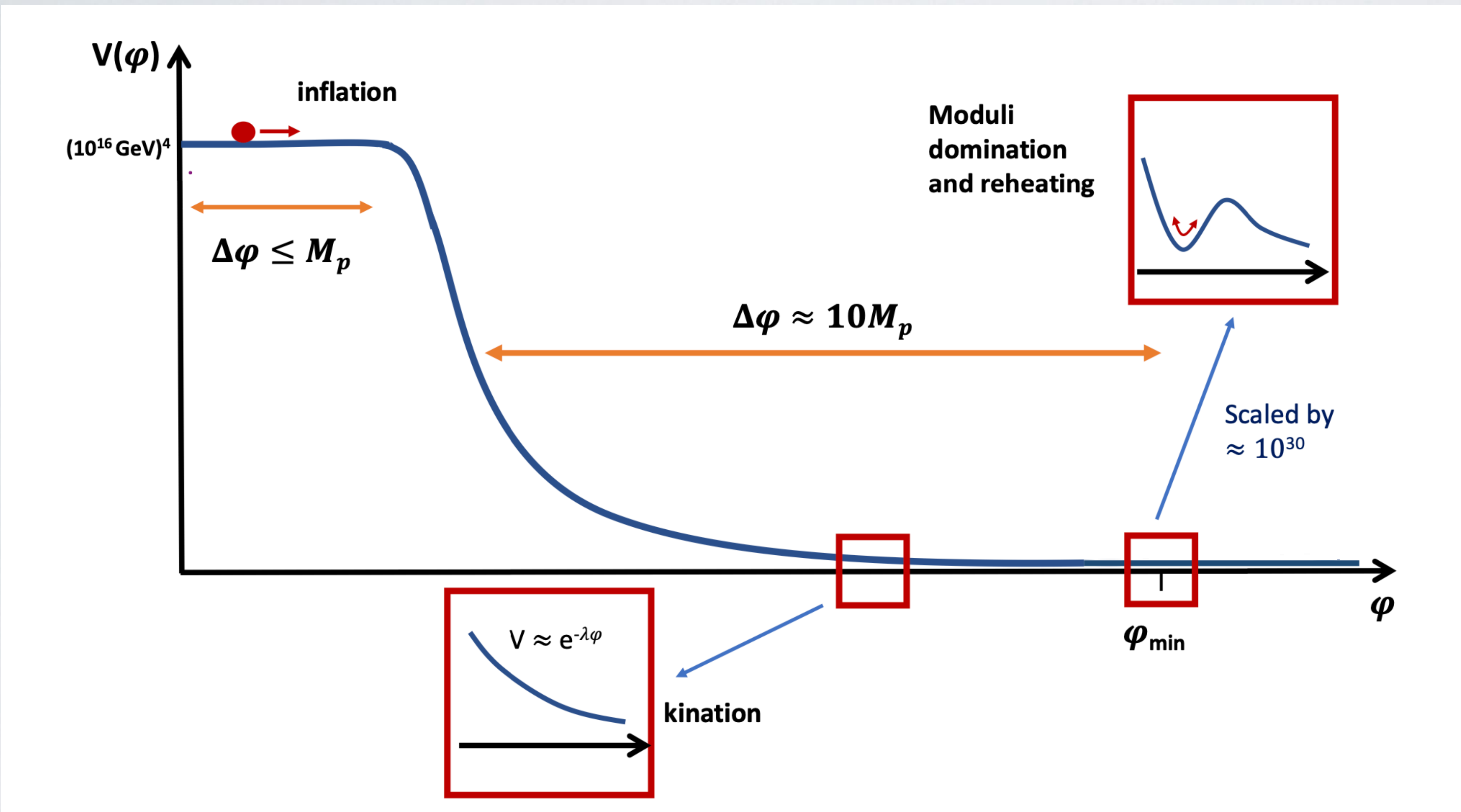
NOVEL COSMOLOGICAL HISTORY



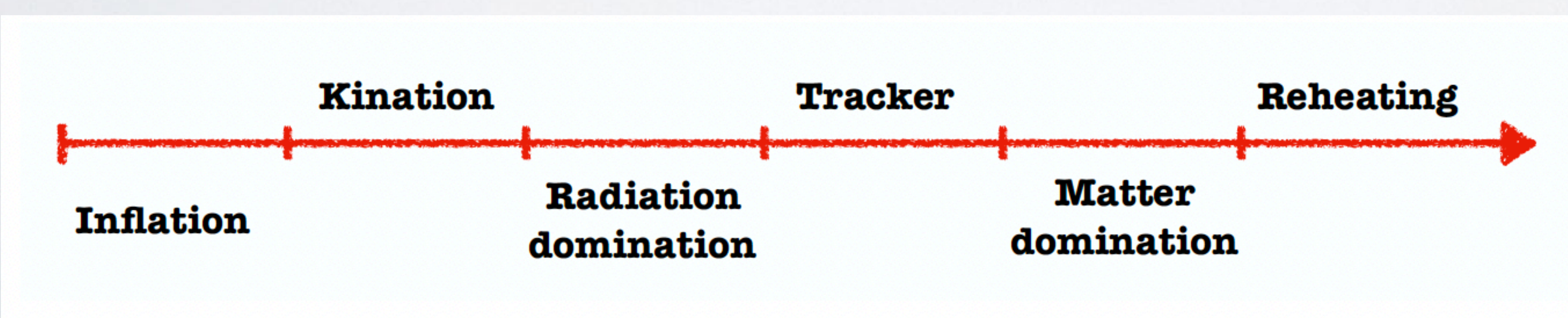
This motivates a distinctive 'stringy' cosmological history quite distinct from the normal assumption of radiation domination after inflation



NOVEL COSMOLOGICAL HISTORY



We know almost NOTHING observationally about the ~ 30 orders in magnitude in time between end of inflation and the beginning of nucleosynthesis!



KINATION EPOCHS

- During kination epoch, kinating field evolves as

$$\Phi(t) = \Phi_0 + \sqrt{\frac{2}{3}} M_P \ln\left(\frac{t}{t_0}\right)$$

- Field moves through $\sim M_P$ in field space each Hubble time

  Long kination epoch implies large transPlanckian field excursions

- String theorists should **care!** - trans-Planckian field excursions $\Delta\Phi \gg M_P$ is home territory

- Novel cosmology: real opportunites for string phenomenology

My talk:
Cosmic Strings

IV. COSMIC SUPERSTRINGS IN EARLY UNIVERSE

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A. VARYING TENSION AND GROWTH OF STRING LOOPS

DYNAMICS OF COSMIC (SUPER)STRINGS

- Cosmic (super)strings long-studied candidate for new stringy cosmologies

Kibble 76 Witten 85
Brandenberger+Vafa 86 Sarangi+Tye 02 Copeland+Polchinski 05

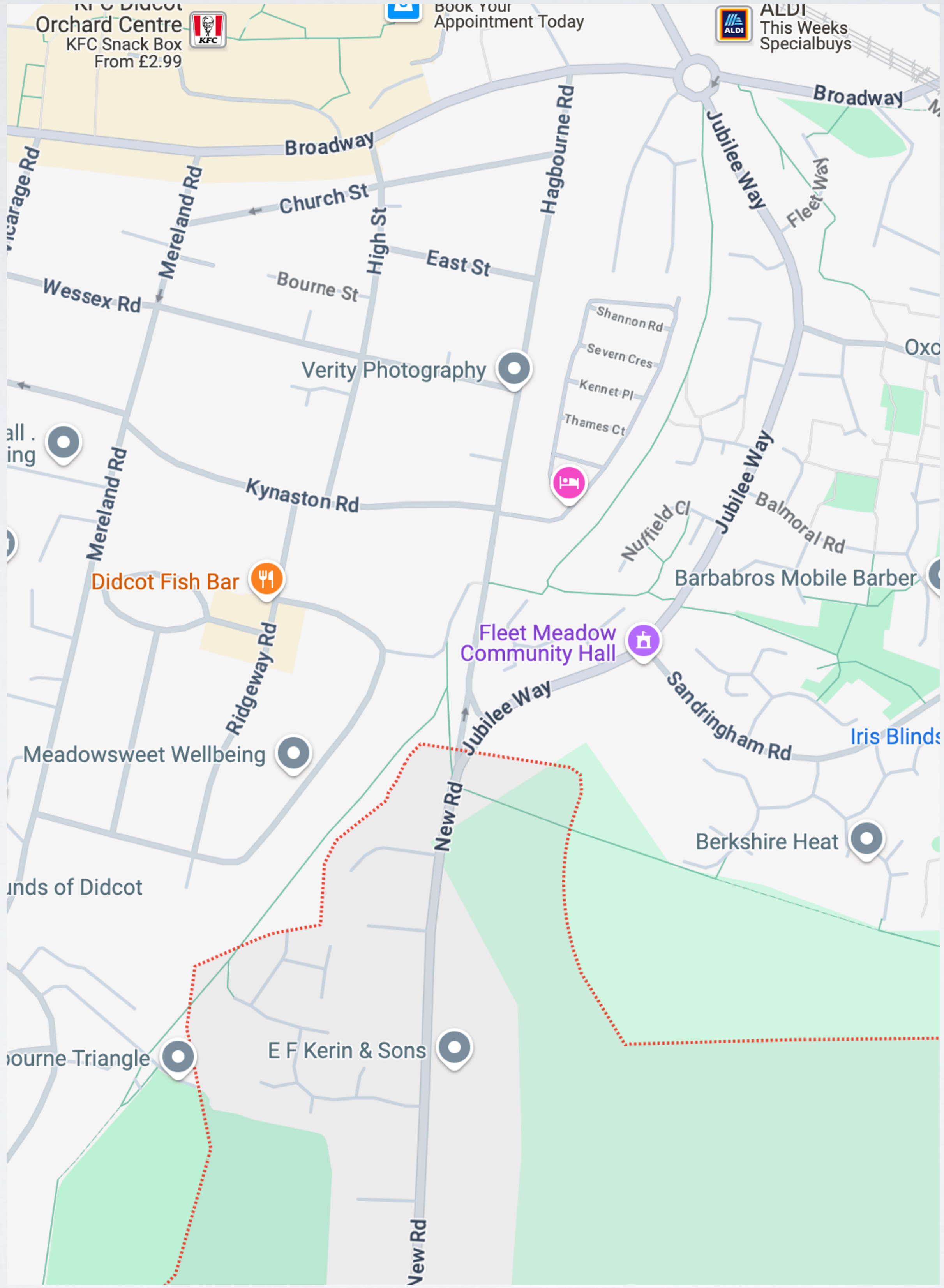
- Dynamics of closed strings set by Nambu-Goto action in fixed spacetime background, μ is the string tension

$$S_{NG} = -\int d^2\xi\,\mu\sqrt{-\gamma}$$

- What are the dynamics? (assuming stability and FRLW metric)

$$ds^2 = dt^2 - a(t)^2\left(dx^2 + dy^2 + dz^2\right)$$

DIDCOT HOUSING POLICY



DIDCOT HOUSING POLICY

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DIDCOT HOUSING POLICY

DYNAMICS OF COSMIC (SUPER)STRINGS (FIXED TENSION)

- Equations of motion follow from NG action

$$x^{\nu\ ;a}_{,a} + \Gamma^{\nu}_{\beta\rho}(g)\gamma^{ad}x^{\beta}_{,d}x^{\rho}_{,a} = 0$$

- Focus on circular string loops

$$X^{\mu}(t,\sigma) = R(t)\big(\cos\sigma, \sin\sigma, 0\big)$$

- Study equations of motion in FLRW background (gauge choice identifies worldsheet and spacetime time)

DYNAMICS OF COSMIC (SUPER)STRINGS (FIXED TENSION)

- Focus on circular string loops

$$X^\mu(t,\sigma) = R(t)\big(\cos\sigma, \sin\sigma, 0\big)$$

- Equations of motion are

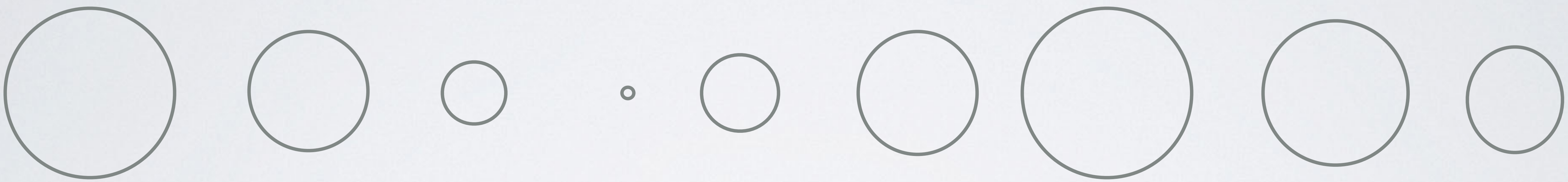
$$\left(\varepsilon = \sqrt{\frac{a^2R^2}{(1-a^2\dot{R}^2)}} \equiv aR_{\max}\right)$$

$$\frac{\dot{\varepsilon}}{\varepsilon} = H - 2a^2\dot{R}^2H \qquad \langle a^2\dot{R}^2\rangle = 1/2$$

$$\ddot{R} + H\dot{R} + \varepsilon^{-2}R + 2H(1-a^2\dot{R}^2)\dot{R} = 0$$

- Loops oscillate with a fixed maximum (physical) size $\boldsymbol{R_{max}}$

EVOLUTION OF A LOOP



Circular string loops oscillate in and out back on themselves at constant physical radius and shrink in comoving coordinates

More complicated exact solutions also exist (Burden, Kibble+Turok)

Loops are left behind as universe expands (and gradually decay by emission of gravitational waves)

DYNAMICS OF COSMIC (SUPER)STRINGS (VARYING TENSION)

- Equations of motion follow from NG action

$$x^{\nu\ ;a}_{,a} + \Gamma^{\nu}_{\beta\rho}(g)\gamma^{ad} x^{\beta}_{,d} x^{\rho}_{,a} + \frac{\mu_{,\rho}}{\mu}\gamma^{ab} x^{\rho}_{,a} x^{\nu}_{,b} - \frac{\mu^{,\nu}}{\mu} = 0,$$

- Focus on circular string loops

$$X^{\mu}(t,\sigma) = R(t)\big(\cos\sigma, \sin\sigma, 0\big)$$

- Study equations of motion in kinating FLRW background (gauge choice identifies worldsheet and spacetime time)

DYNAMICS OF COSMIC (SUPER)STRINGS (VARYING TENSION)

- Focus on circular string loops

$$X^\mu(t,\sigma) = R(t)\big(\cos\sigma, \sin\sigma, 0\big)$$

- Equations of motion are

$$\varepsilon = \sqrt{\frac{a^2R^2}{(1-a^2\dot{R}^2)}} \equiv aR_{\max}$$

$$\frac{\dot{\varepsilon}}{\varepsilon} = H - a^2\dot{R}^2\left(2H + \frac{\dot{\mu}}{\mu}\right) \qquad \langle a^2\dot{R}^2\rangle = 1/2$$

$$\ddot{R} + H\dot{R} + \varepsilon^{-2}R + \left(2H + \frac{\dot{\mu}}{\mu}\right)(1-a^2\dot{R}^2)\dot{R} = 0$$

- High-frequency oscillation at (physical) amplitude R_{max} but….

DYNAMICS OF COSMIC (SUPER)STRINGS (VARYING TENSION)

- Equations of motion are

$$\varepsilon = \sqrt{\frac{a^2R^2}{(1 - a^2\dot{R}^2)}} \equiv aR_{\max}$$

$$\frac{\dot{\varepsilon}}{\varepsilon} = H - a^2\dot{R}^2\left(2H + \frac{\dot{\mu}}{\mu}\right)$$

$$\langle a^2\dot{R}^2\rangle = 1/2$$

- Decreasing tension causes loops to grow with cosmic time

- Right hand side of equation determines precisely how loops compared to scale factor (cf $\frac{\dot{a}}{a} = H$)

DYNAMICS OF COSMIC (SUPER)STRINGS (VARYING TENSION)

- Equations of motion are

$$\varepsilon = \sqrt{\frac{a^2R^2}{(1 - a^2\dot{R}^2)}} \equiv aR_{\text{max}}$$

$$\frac{\dot{\varepsilon}}{\varepsilon} = H - a^2\dot{R}^2 \cancel{\left(2H + \frac{\dot{\mu}}{\mu}\right)}$$

$$\langle a^2\dot{R}^2 \rangle = 1/2$$

- Decreasing tension causes loops to grow with cosmic time

- If crossed out term vanishes, oscillating loops grow precisely with the scale factor (cf $\frac{\dot{a}}{a} = H$)

DYNAMICS OF COSMIC (SUPER)STRINGS (VARYING TENSION)

- Equations of motion are

$$\varepsilon = \sqrt{\frac{a^2R^2}{(1-a^2\dot{R}^2)}} \equiv aR_{\max}$$

$$\frac{\dot{\varepsilon}}{\varepsilon} = H - a^2\dot{R}^2\left(2H + \frac{\dot{\mu}}{\mu}\right) \qquad \langle a^2\dot{R}^2\rangle = 1/2$$

- When $2H + \frac{\dot{\mu}}{\mu} < 0$, oscillating loops grow faster than the scale factor **and will percolate given enough time**

KINATION AND TIME-VARYING TENSION

- We want to make $2H + \frac{\dot{\mu}}{\mu}$ as negative as possiblr
- This requires

  (a) $H \equiv \frac{\dot{a}}{a}$ as small as possible

  (b) $\frac{\dot{\mu}}{\mu}$ as large and negative as possible

- Kination epochs are ideal as

  (a) $a(t) \sim t^{1/3}$ and so growth is as slower than any other fluid

  (b) All energy is in kinetic evolution of a modulus and so maximises rate of change of tension vev

KINATION AND TIME-VARYING TENSION

- During volume modulus kination, volume grows with time

$$\frac{\mathcal{V}}{\mathcal{V}_0} = \frac{t}{t_0}$$

- For superstrings, $G\mu \sim m_s^2$ and so $\mu \propto t^{-1}$ using standard relationship

$$m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}$$

- It follows that

$$2H + \frac{\dot{\mu}}{\mu} = -H < 0$$

and so loops of fundamental strings grow faster than the scale factor!

- Loops of fundamental strings grow in comoving coordinates and can percolate!

PERCOLATING SUPERSTRINGS

- During kination, scale factor and loop radius grow as

$$a(t) \sim t^{1/3}$$
$$R_{max}(t) \sim t^{1/2}$$

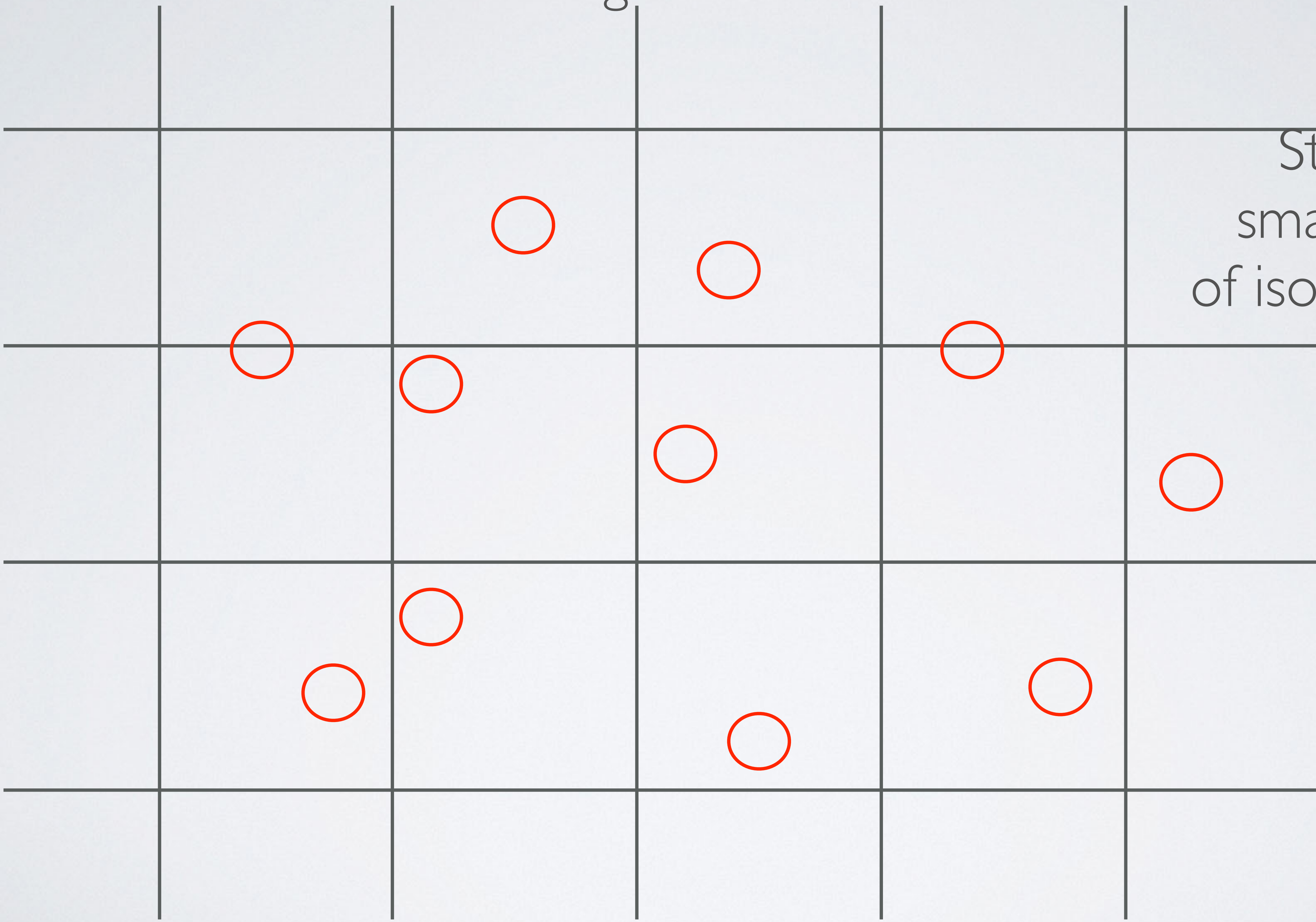
- In comoving coordinates,

$$R_{max,comoving} \sim t^{1/6} \sim \left(\frac{\mathscr{V}_f}{\mathscr{V}_i}\right)^{1/6}$$

- Long kination epochs (closely tie to vacua in asymptotic region of moduli space) essential to give percolation

PERCOLATING SUPERSTRINGS

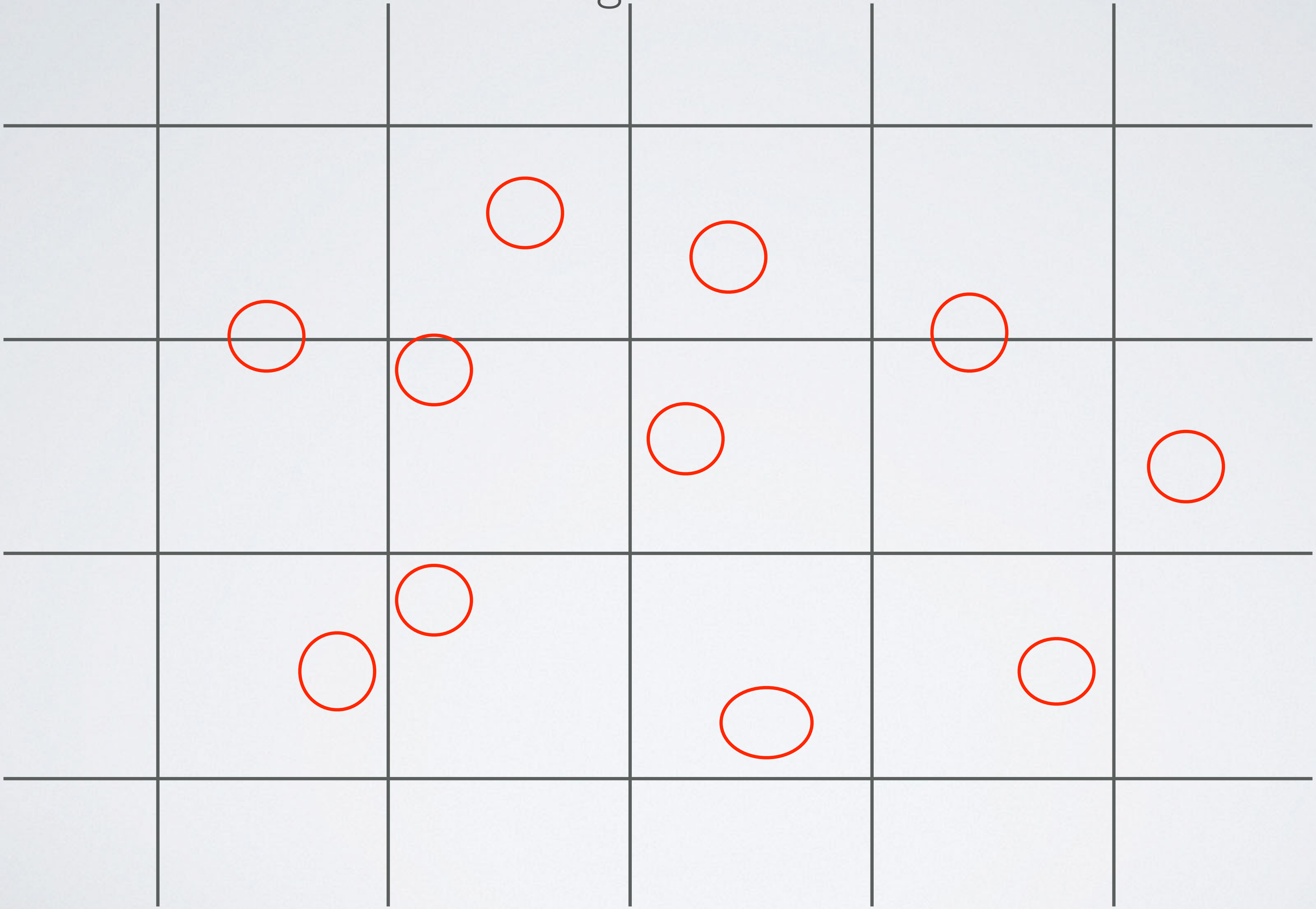
Fixed comoving coordinates



Start with
small number
of isolated strings

PERCOLATING SUPERSTRINGS

Fixed comoving coordinates



PERCOLATING SUPERSTRINGS

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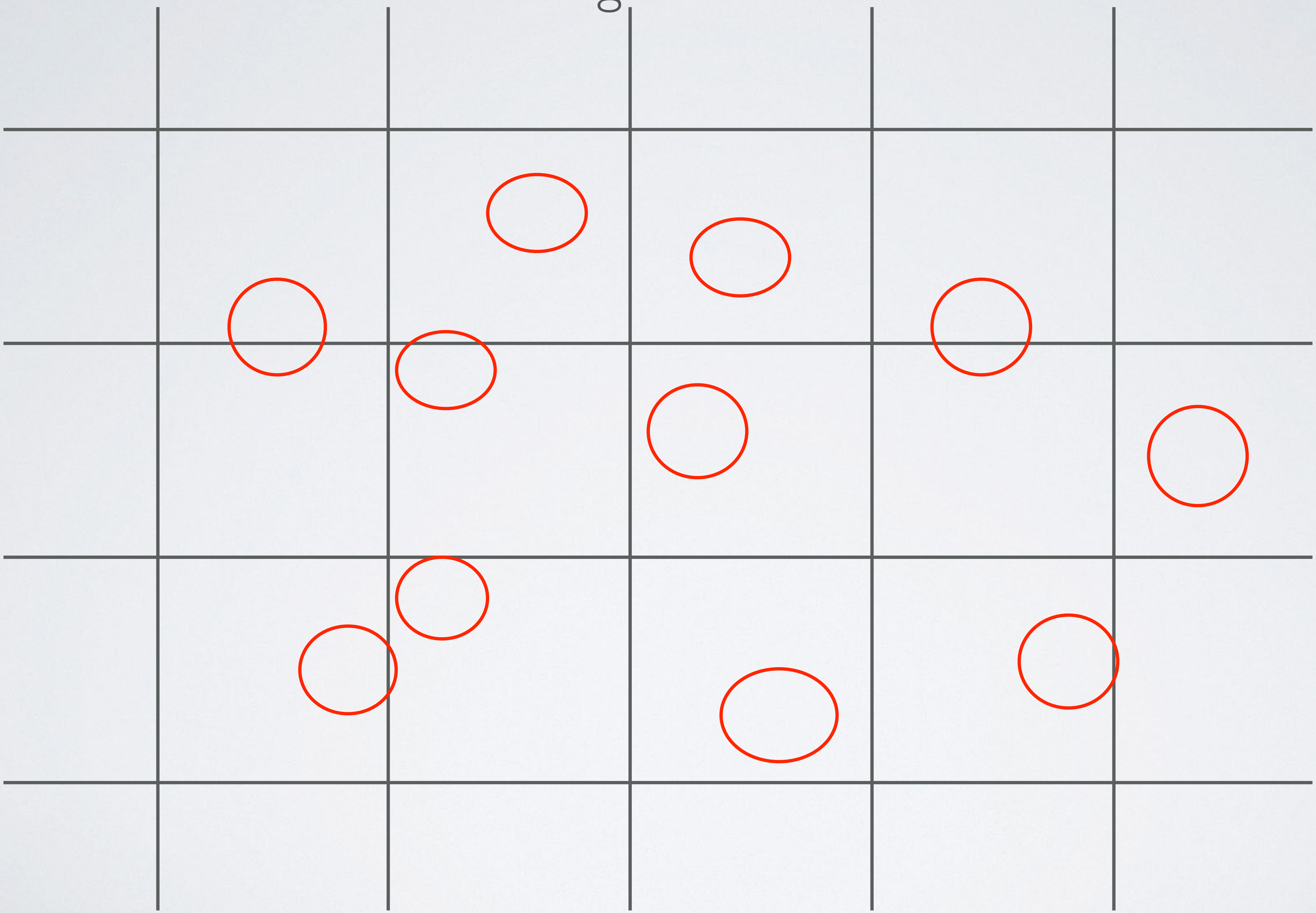

PERCOLATING SUPERSTRINGS

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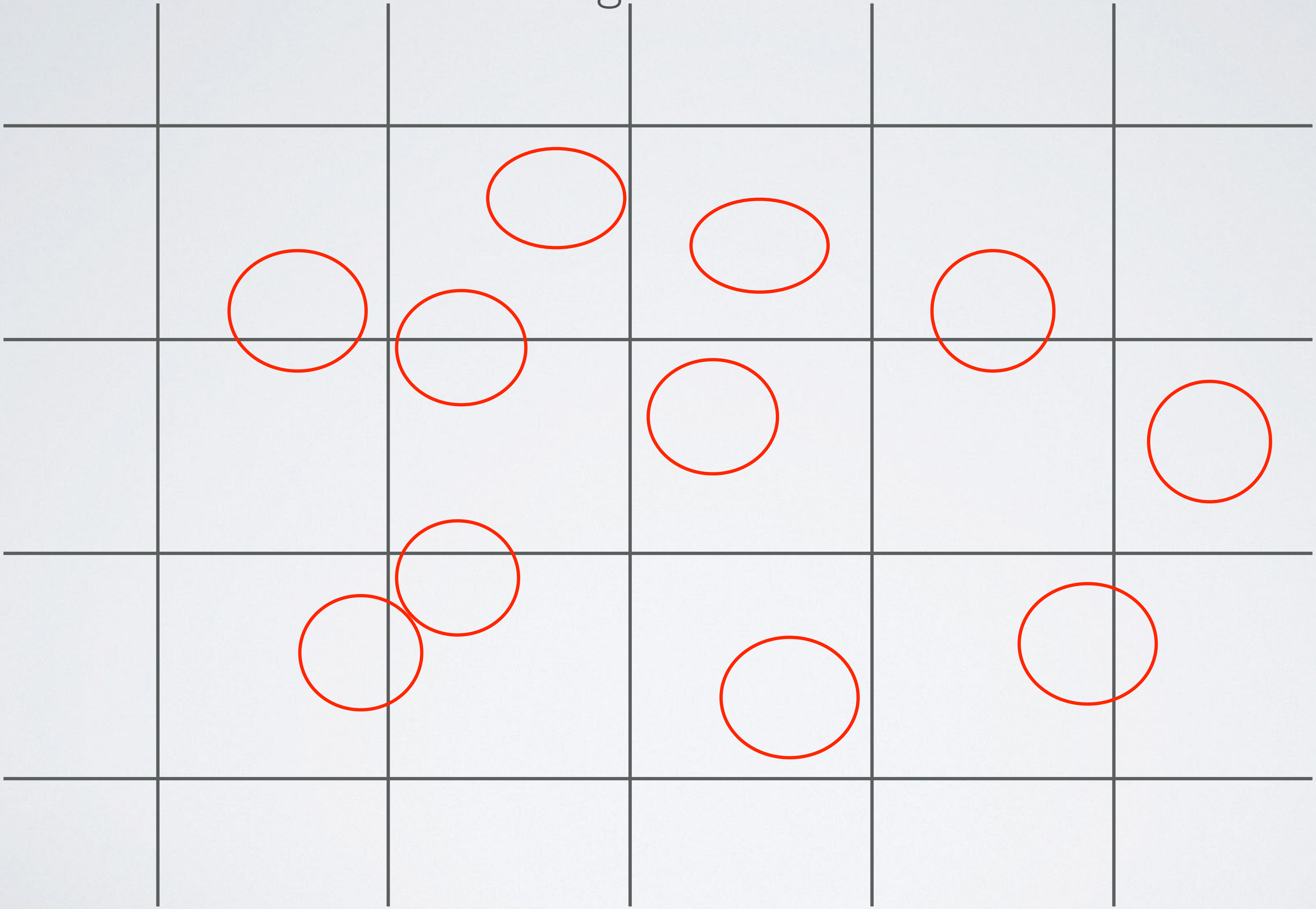
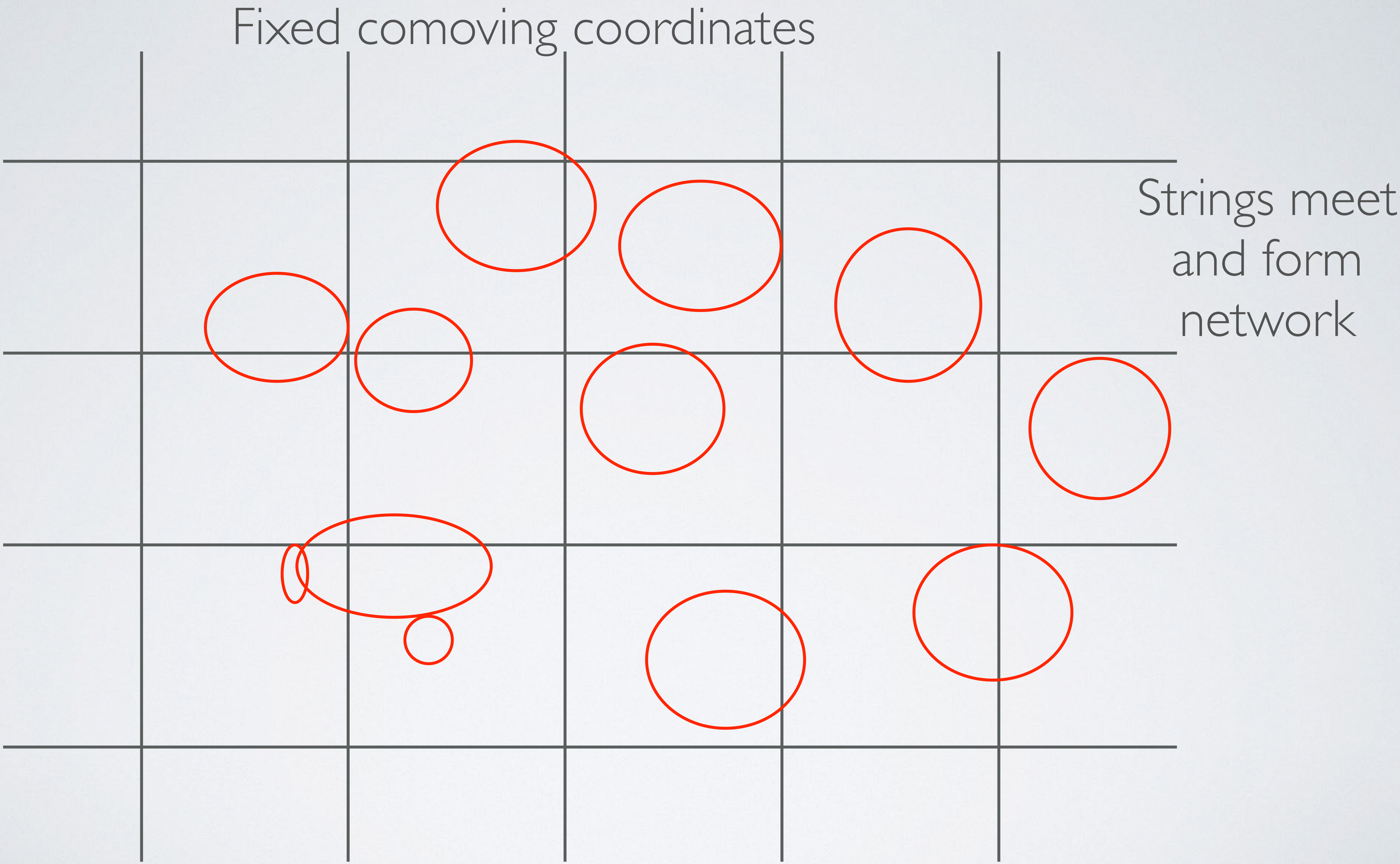


PERCOLATING SUPERSTRINGS



IV. COSMIC SUPERSTRINGS IN EARLY UNIVERSE

B. SUPERSTRING PHASES

Sanchez-Gonzales, JC, Copeland, Hardy, 2505.14187

SUPERSTRING PHASES

- Consider a scalar field (volume modulus) rolling on an exponential potential,
$$V = V_0 e^{-\lambda\Phi}$$
- For string theory LVS potential, $\lambda = \sqrt{\frac{27}{2}}$
- What is the stable attractor?

LOOP ENERGY DENSITY

Energy in an individual loop is set as

$$E_{loop} = l \times \mu$$

As $l \propto \sqrt{\dfrac{\mu_0}{\mu(t)}}$, overall energy density in loops scales as

$$\rho_{loops} \sim \frac{1}{a^3}\sqrt{\frac{\mu(t)}{\mu_0}}$$

LOOP ENERGY DENSITY

During kination,

$$\rho_{loops} \sim \frac{1}{a^{9/2}}$$

During radiation tracker,

$$\rho_{loops} \sim \frac{1}{a^{11/3}}$$

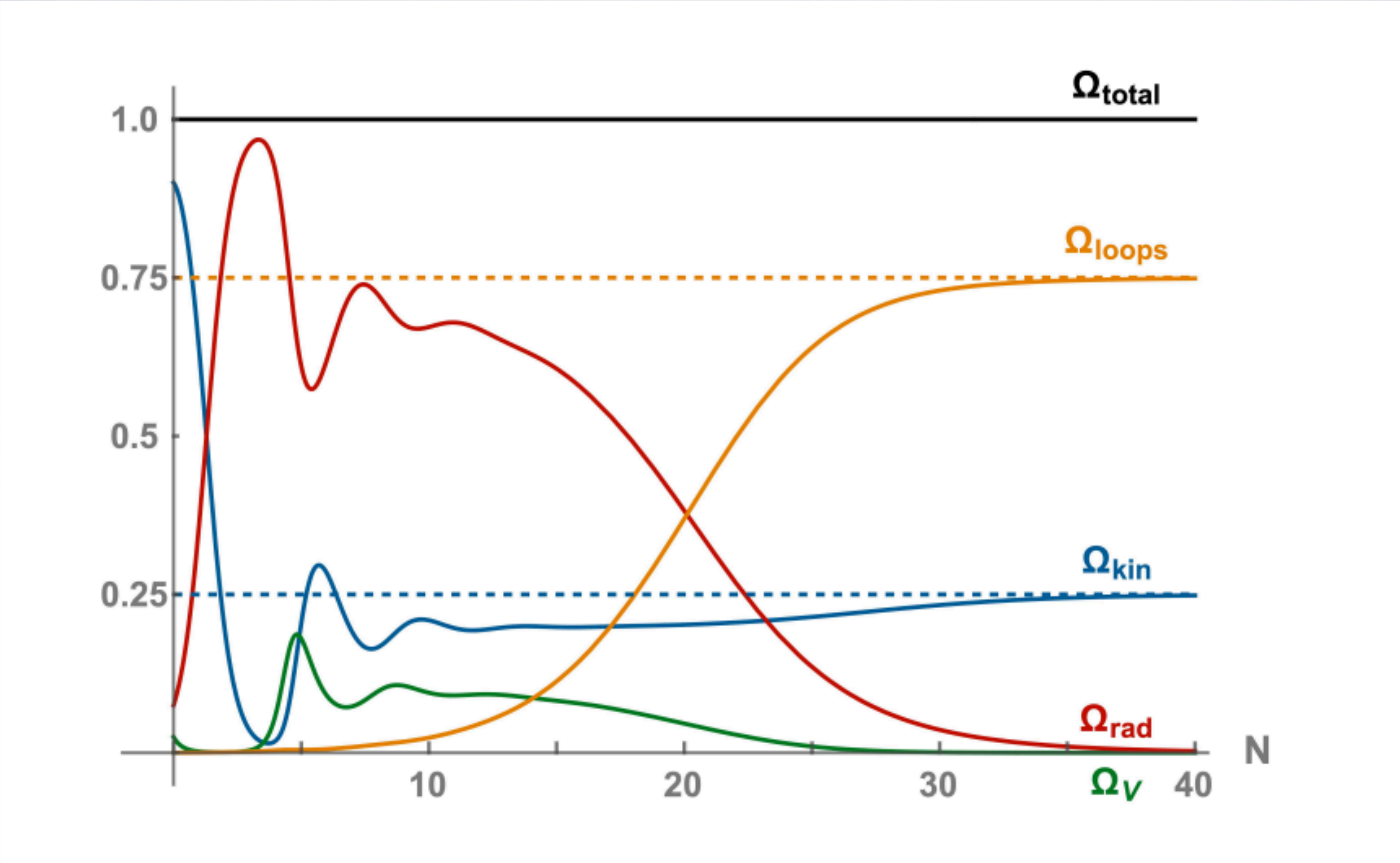
LOOP ENERGY DENSITY

Loop energy density grows relative to background and stable attractor is a loop tracker with

$$\Omega_{loops} = \frac{3}{4}, \Omega_{kin} = \frac{1}{4}$$

Post-inflationary tracker with three-quarters of universe energy density in form of superstrings!

LOOP TRACKER



CONCLUSIONS

- Universe between inflation and nucleosynthesis is poorly constrained — opportunity for string cosmology
- Evolution of volume modulus causes fundamental string loops to grow and they can percolate into a cosmic string network
- Also a novel post-inflationary string loop tracker with 75% of universe energy density in form of superstring loops
- With LVS final vacuum, string network today with $G\mu \sim 10^{-10}$
- Such a fundamental cosmic string network with $10^{-7} \lesssim G\mu \lesssim 10^{-11}$ - in reach of upcoming experiments (cf NANOGrav)