PERCOLATING COSMIC STRING NETWORKS FROM KINATION

Joseph Conlon

String Pheno 2024
Padua

(Talk based on JC, Copeland, Hardy, Sanchez-Gonzales 2406.12637, also see Apers, JC, Copeland, Mosny, Revello 2401.04064)

Parallel Thursday 2.30pm

Parallel Thursday 2.45pm

WHERE IS THE CENTRE OF THE WORLD?

- N=0 supersymmetry
  Hierarchies
  Weak couplings

Strong coupling

$$AdS_5 \times S^5$$

$$g_s \sim 1, \text{Volume} \sim l_s^6$$

Black hole entropy

Dualities

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

Landau-Ginzburg models

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

ASYMPTOTICS OF MODULI SPACE

Cosmology

Supersymmetry Breaking

AdS Vacua - LVS, DGKT

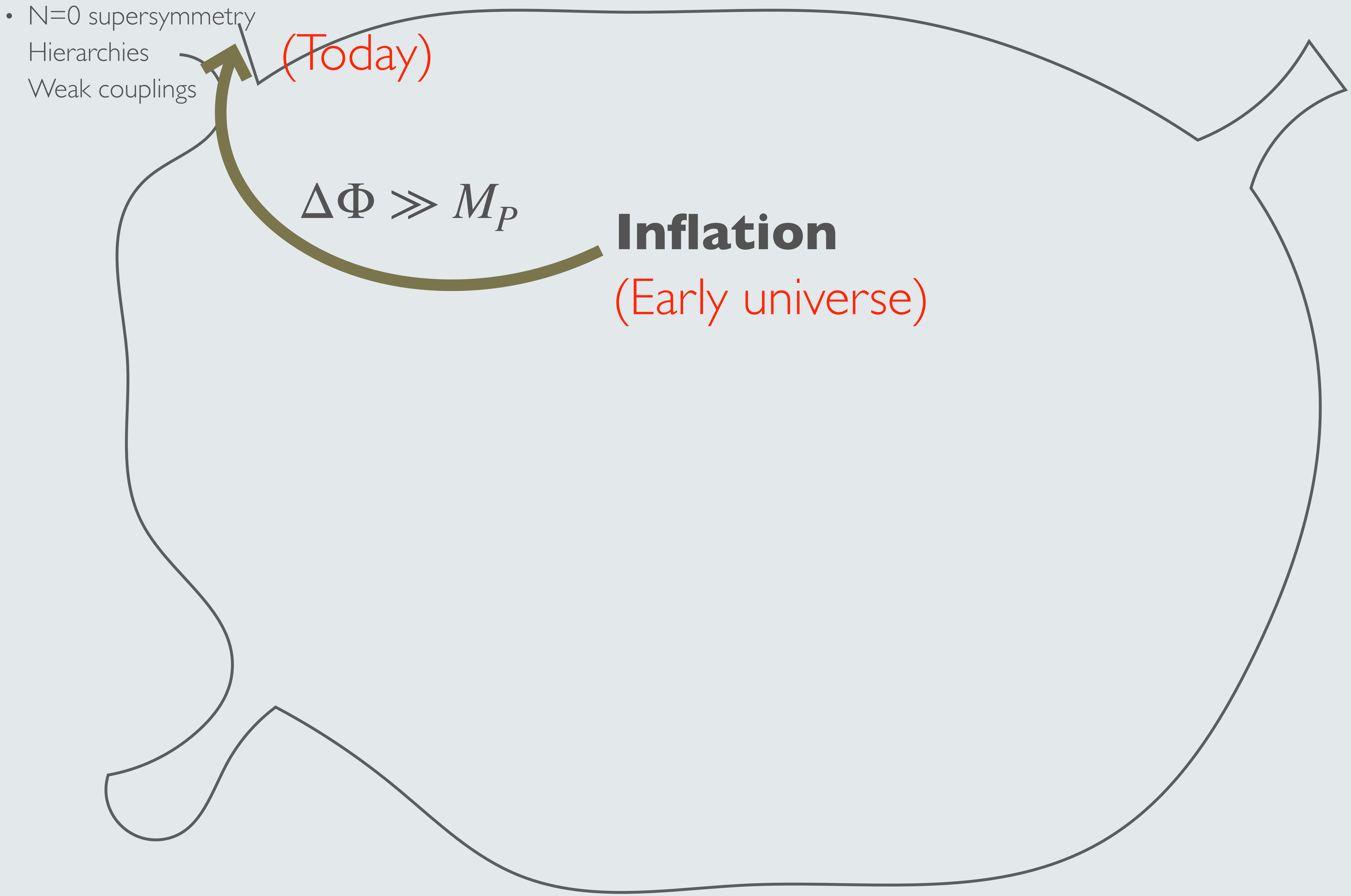
Moduli and Standard Model spectra

Axions

Dark Energy/Quintessence

Many exciting talks this week - Lüst, Halverson, Pedro, Vafa, Valenzuela, Blumenhagen, Marchesano, Parameswaran

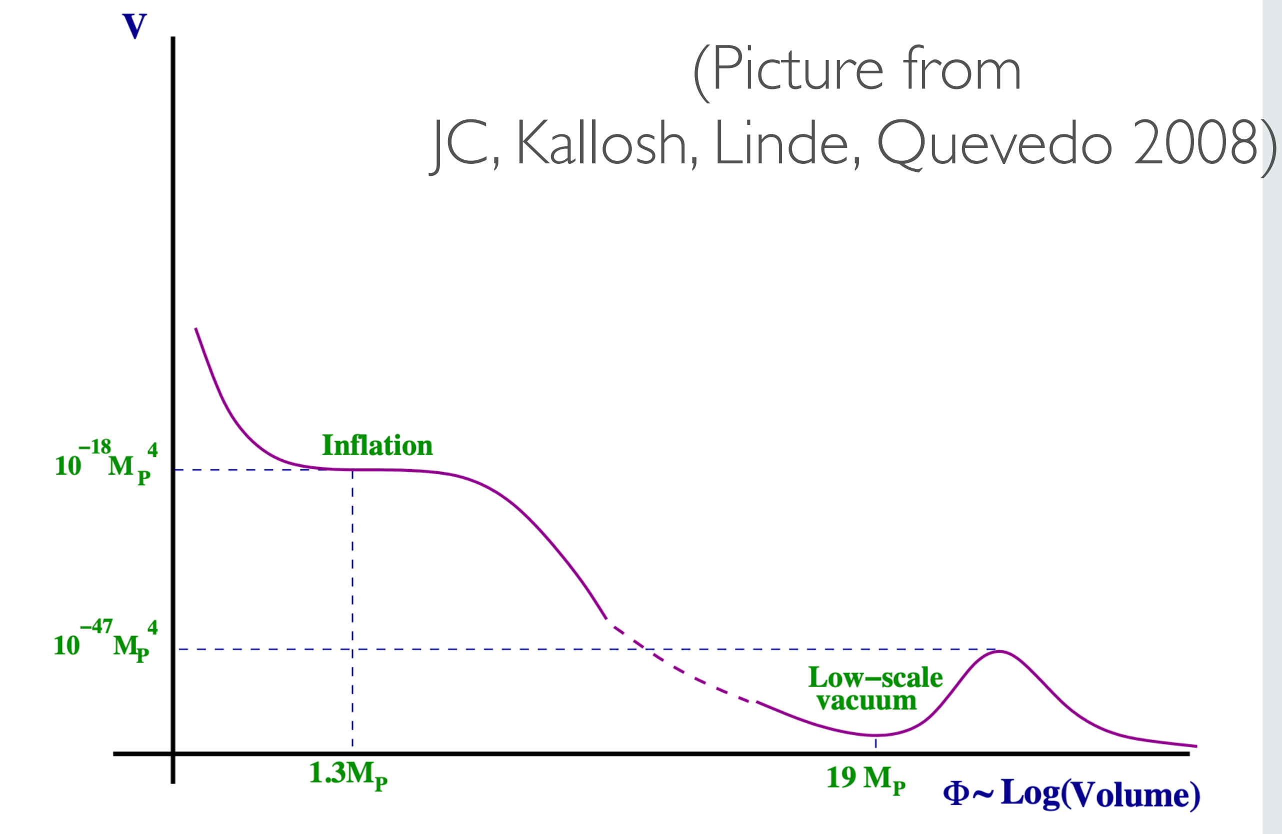
GETTING TO THE CENTRE OF THE WORLD



GETTING TO THE END OF THE WORLD

- We assume we start with an inflationary model of <your favourite model> and end with a vacuum of <my favourite vacuum>

- Talk is about the middle: route from end of inflation to vacuum near the boundaries of moduli space



(Picture from JC, Kallosh, Linde, Quevedo 2008)

- After inflation, field starts rolling down exponential slope

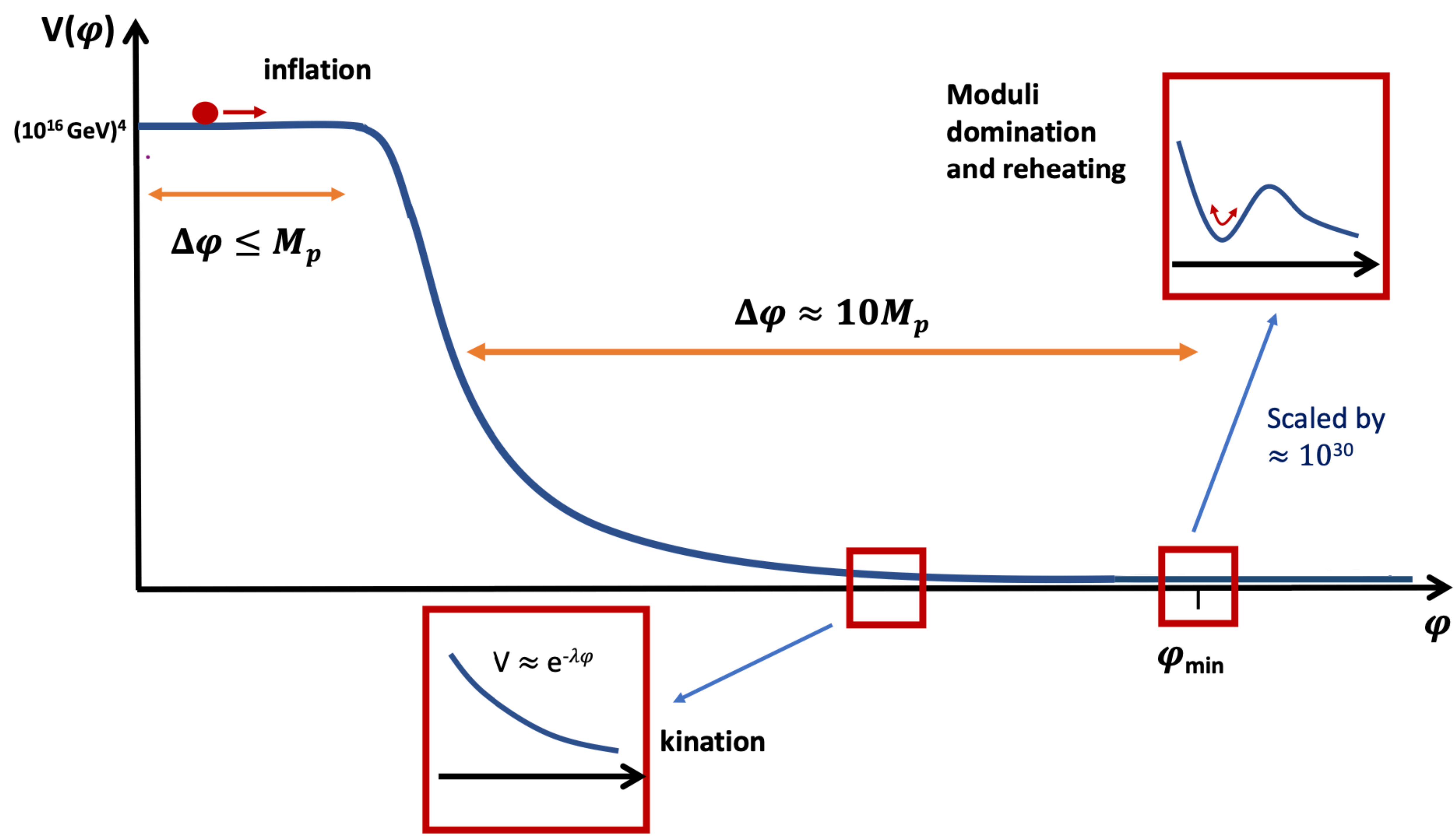
$$V \sim V_0 \exp\left(-\sqrt{\frac{27}{2}}\frac{\Phi}{M_P}\right)$$

(exponent as in LVS, but not material)

- Universe enters a *kination* epoch

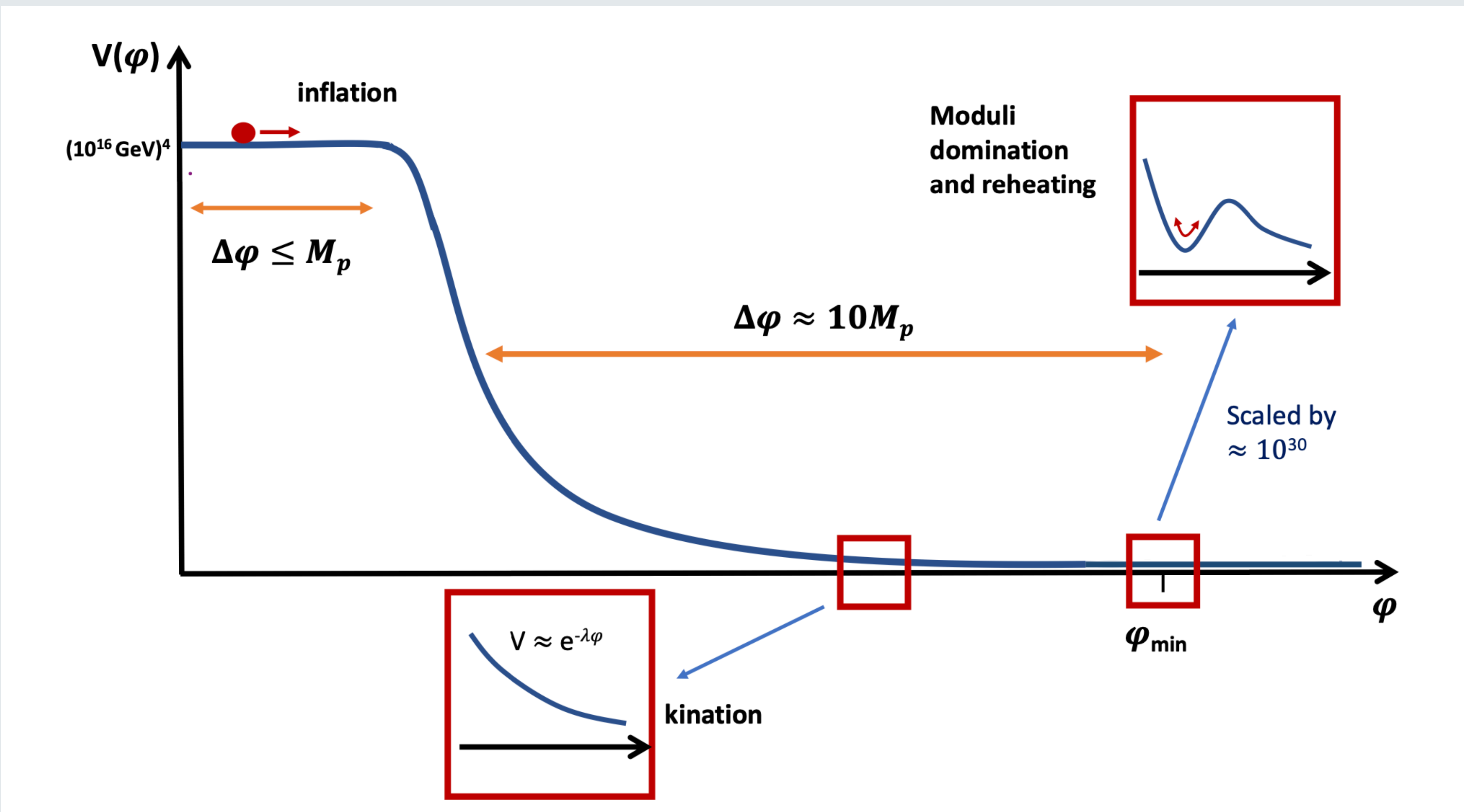
$$a(t) \sim t^{1/3}, \qquad \rho_{KE} \sim \frac{1}{a(t)^6}, \qquad \rho_\gamma \sim \frac{\epsilon}{a(t)^4}$$

GETTING TO THE END OF THE WORLD

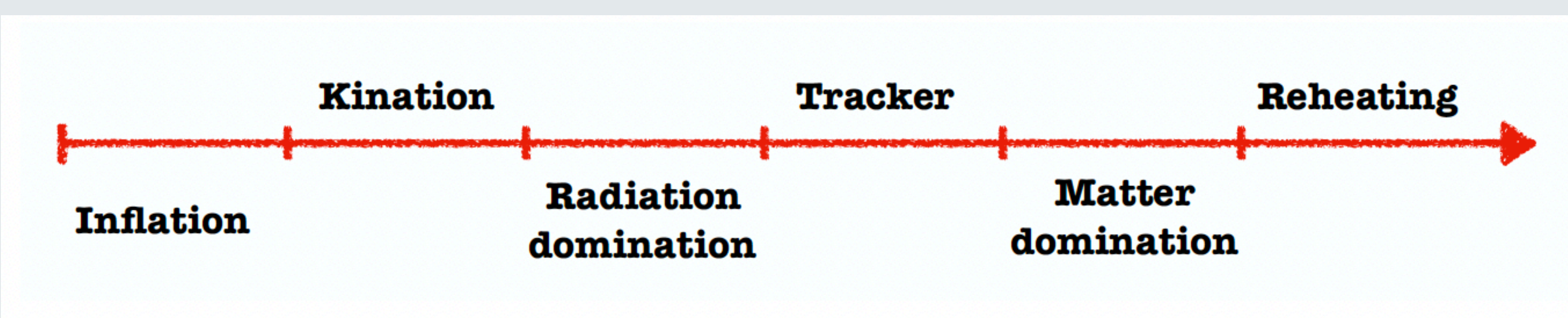


From review 2303.04819 Cicoli, JC, Maharana, Parameswaran, Quevedo, Zavala

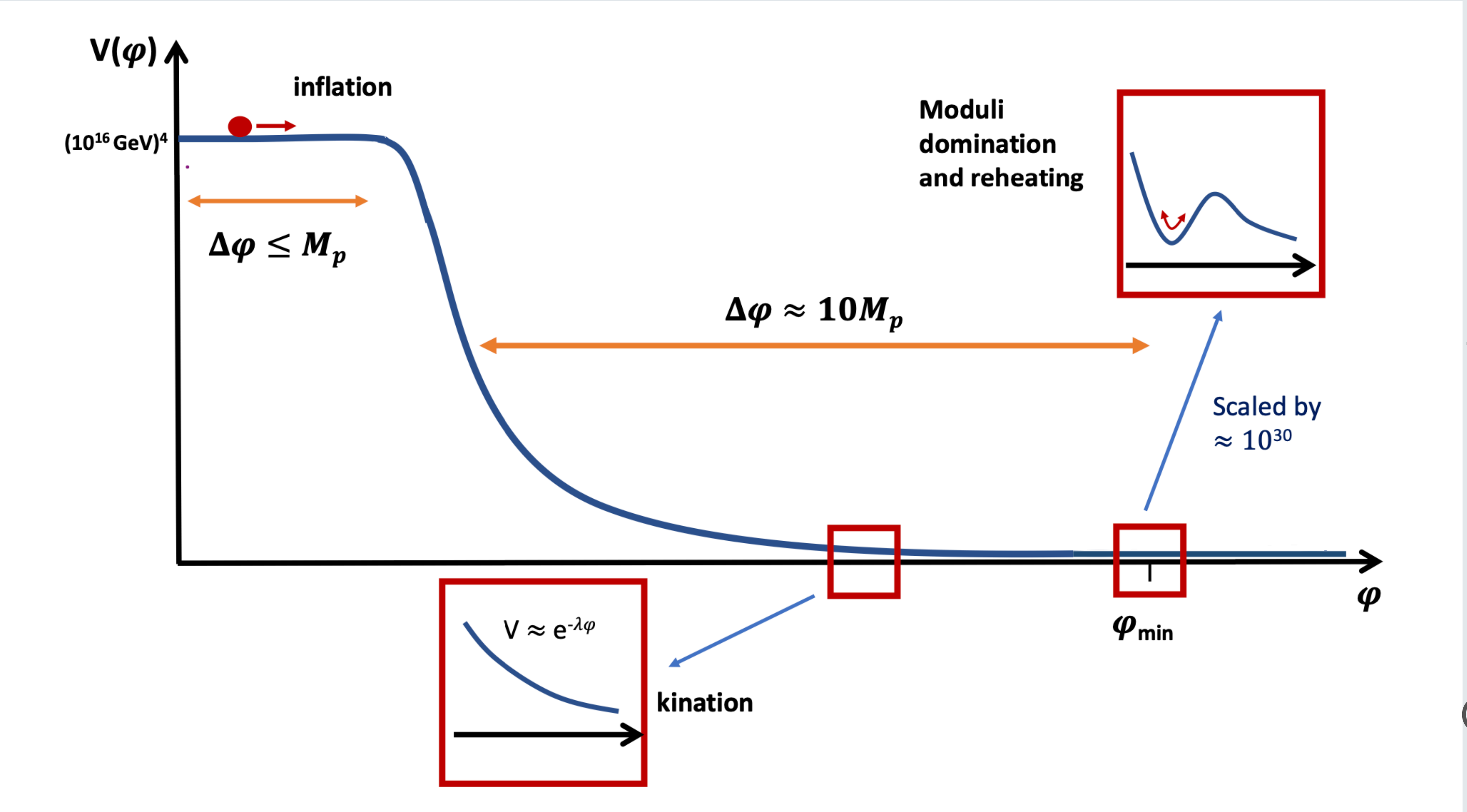
NOVEL COSMOLOGICAL HISTORY



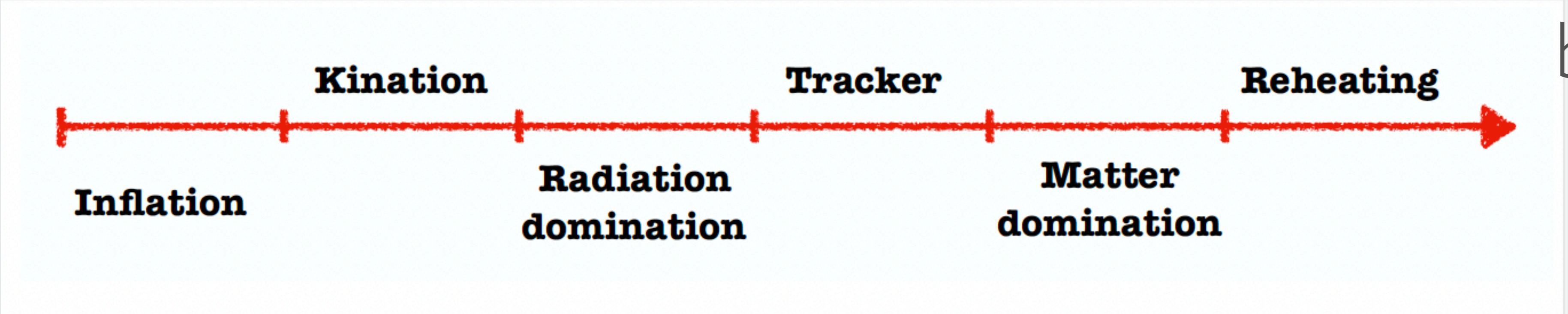
This motivates a distinctive 'stringy' cosmological history quite distinct from the normal assumption of radiation domination after inflation



NOVEL COSMOLOGICAL HISTORY



First half of the universe (on a log scale) is unconstrained: great opportunity for string theory



Many aspects discussed in Thursday parallel talks by Fien Apers and Filippo Revello

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

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)

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

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

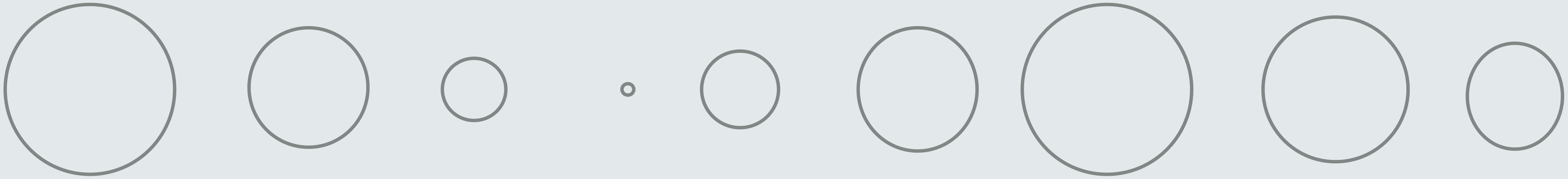
$$\left(\varepsilon = \sqrt{\frac{a^2R^2}{(1 - a^2\dot{R}^2)}} \equiv aR_{\max}\right)$$

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

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

- Loops oscillate with a fixed maximum (physical) size 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)

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

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

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

- 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

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

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

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

- Decreasing tension causes loops to grow with cosmic time

- 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

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

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

- 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

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

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

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

- 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

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

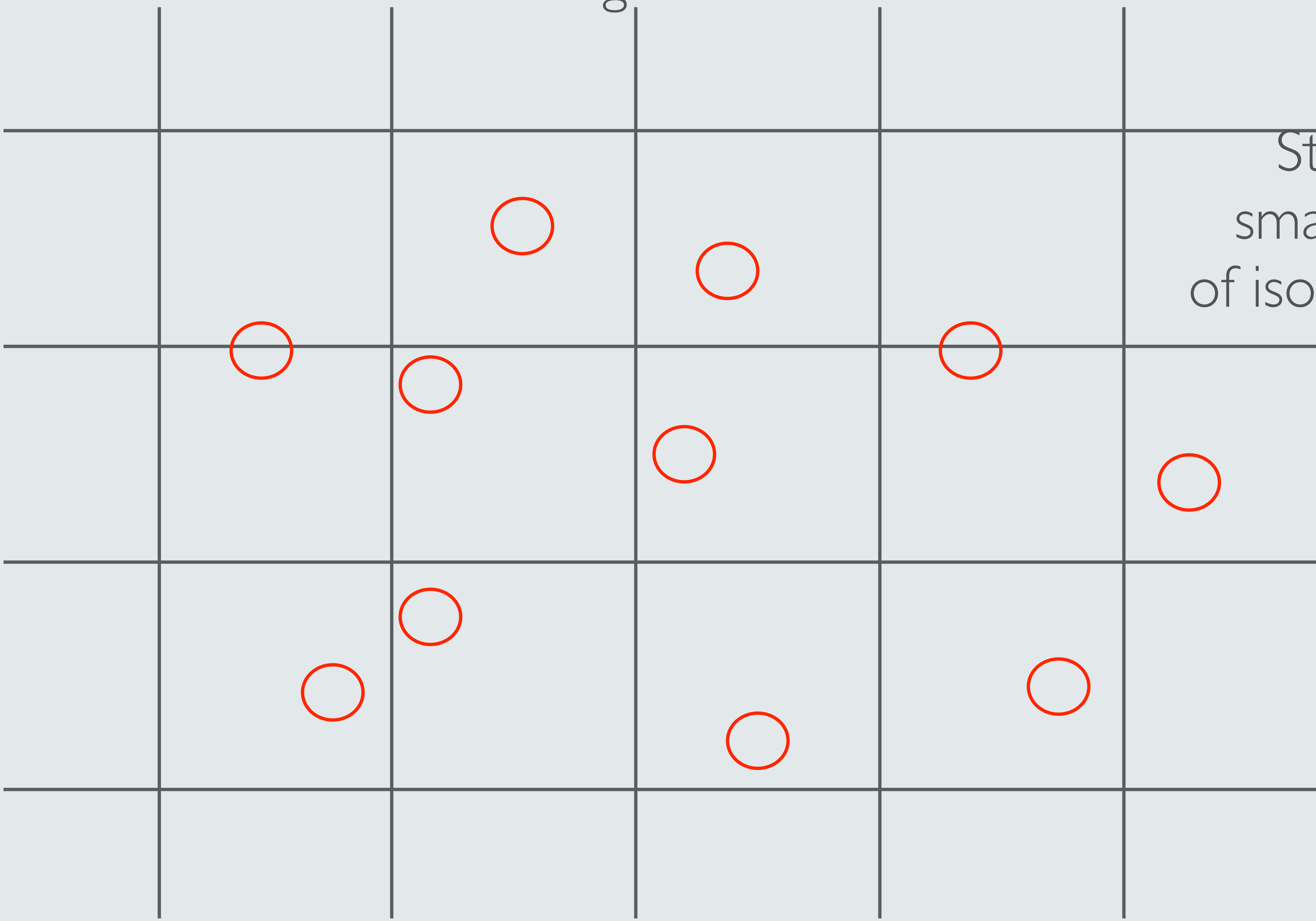
- In comoving coordinates,

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

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

PERCOLATING SUPERSTRINGS

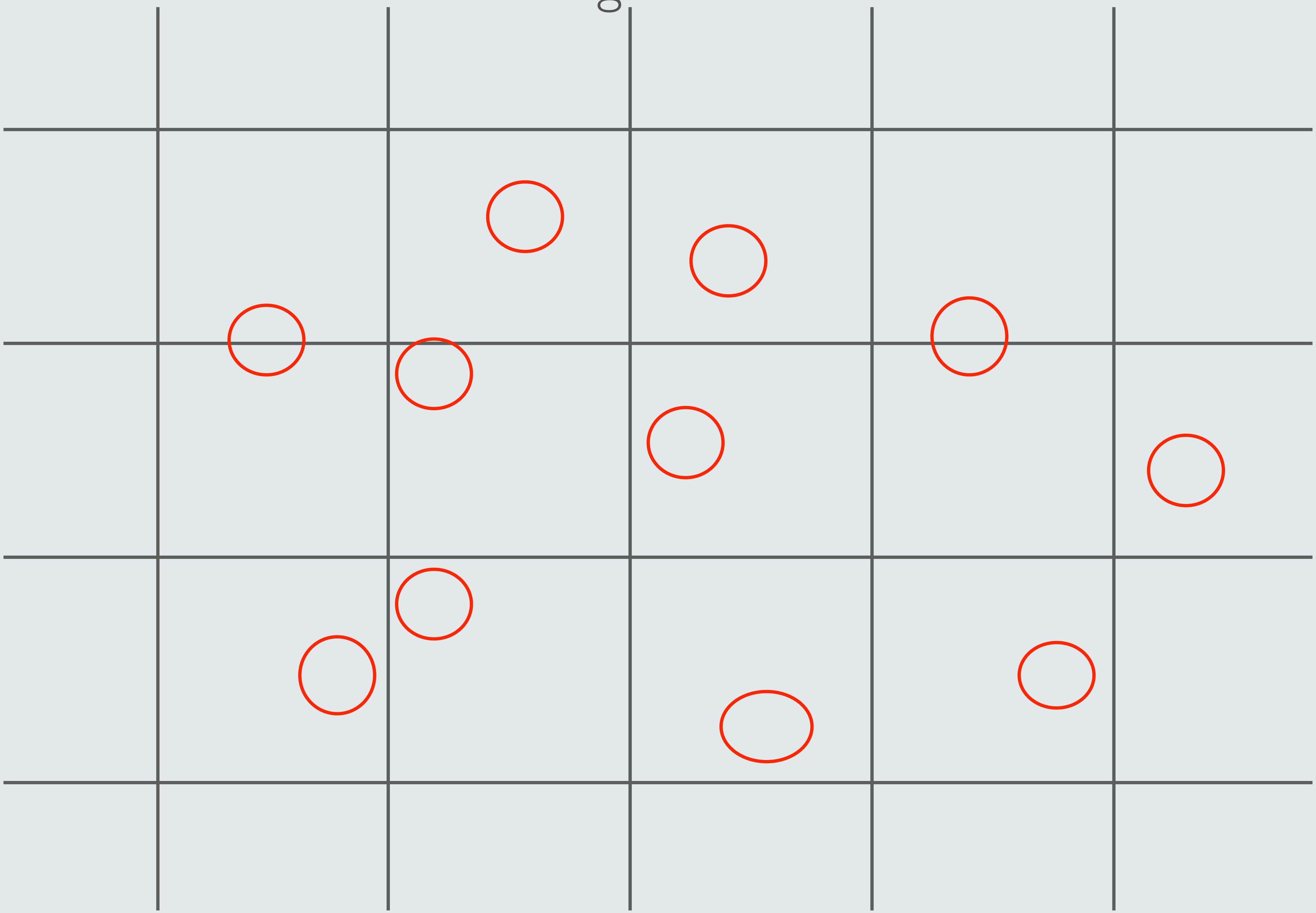
Fixed comoving coordinates



Start with
small number
of isolated strings

PERCOLATING SUPERSTRINGS

Fixed comoving coordinates



PERCOLATING SUPERSTRINGS

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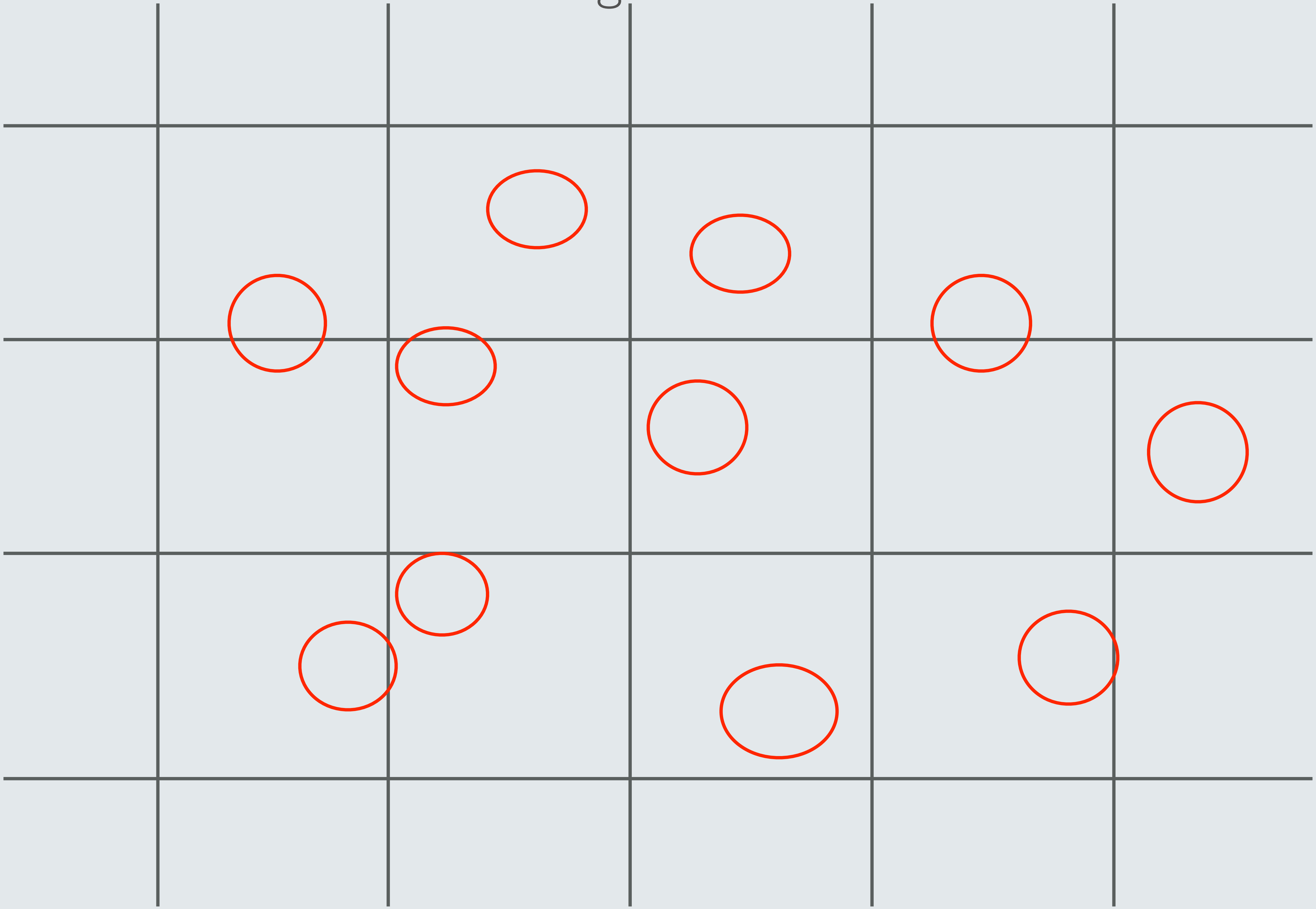

PERCOLATING SUPERSTRINGS

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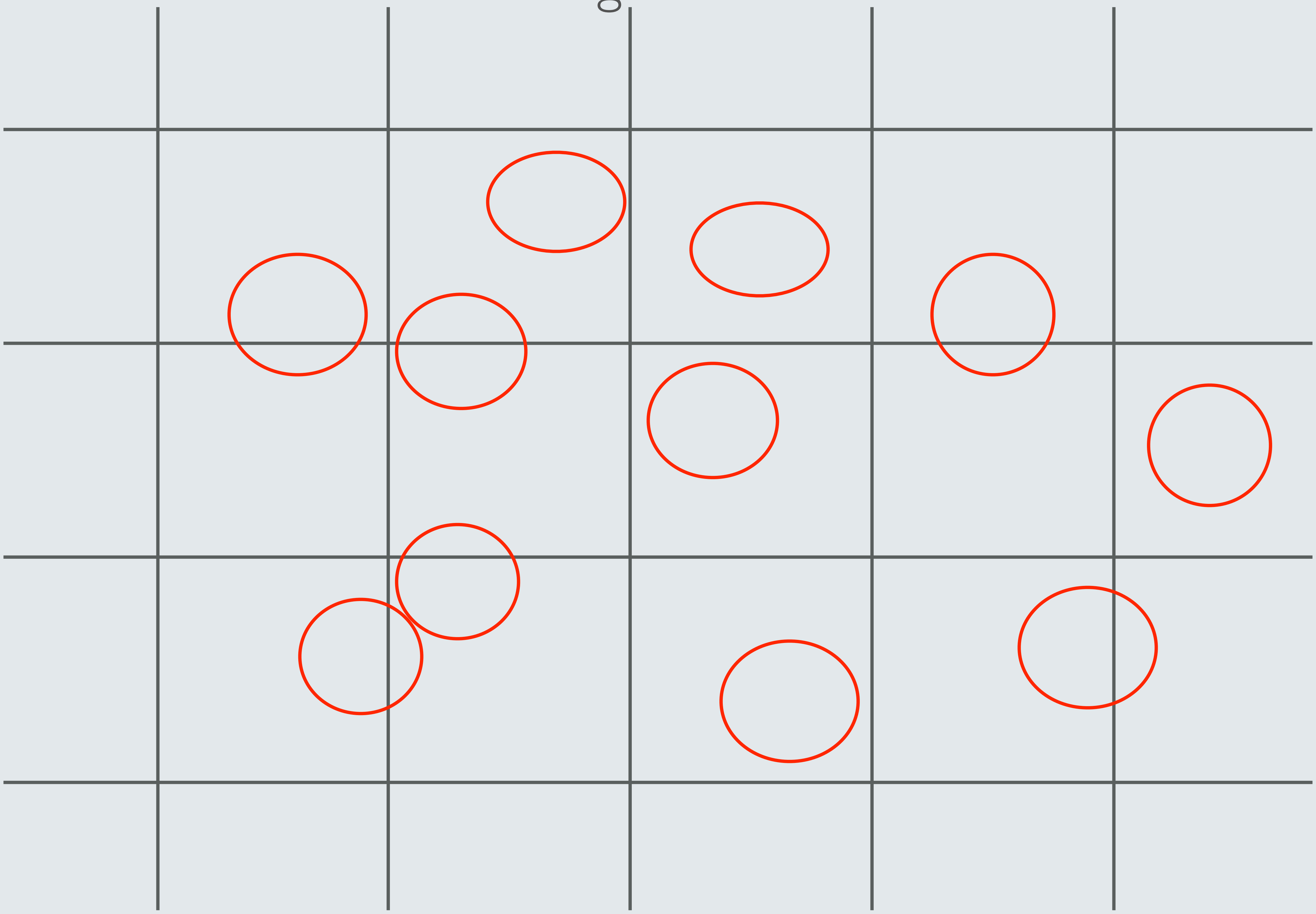
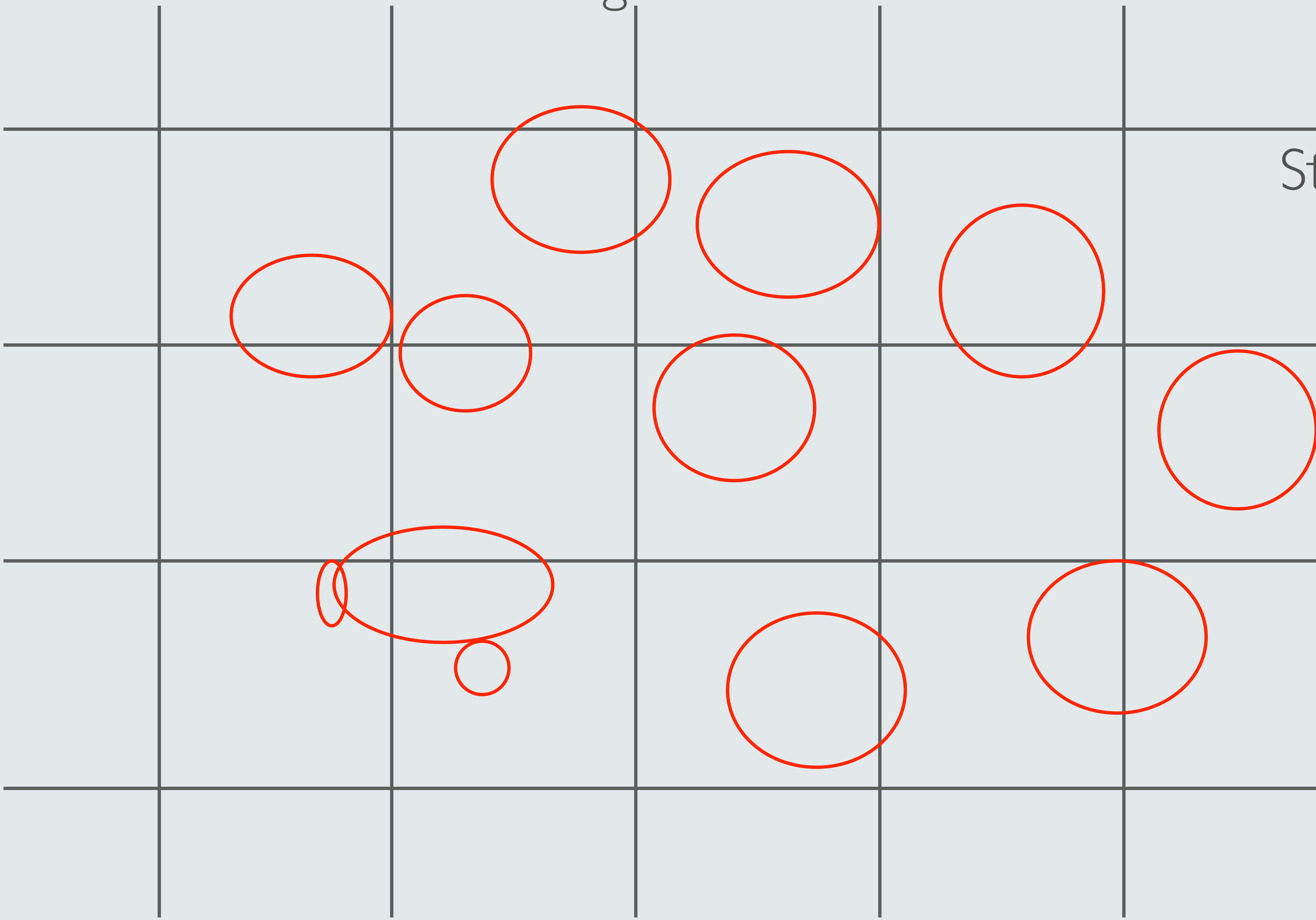


PERCOLATING SUPERSTRINGS

Fixed comoving coordinates



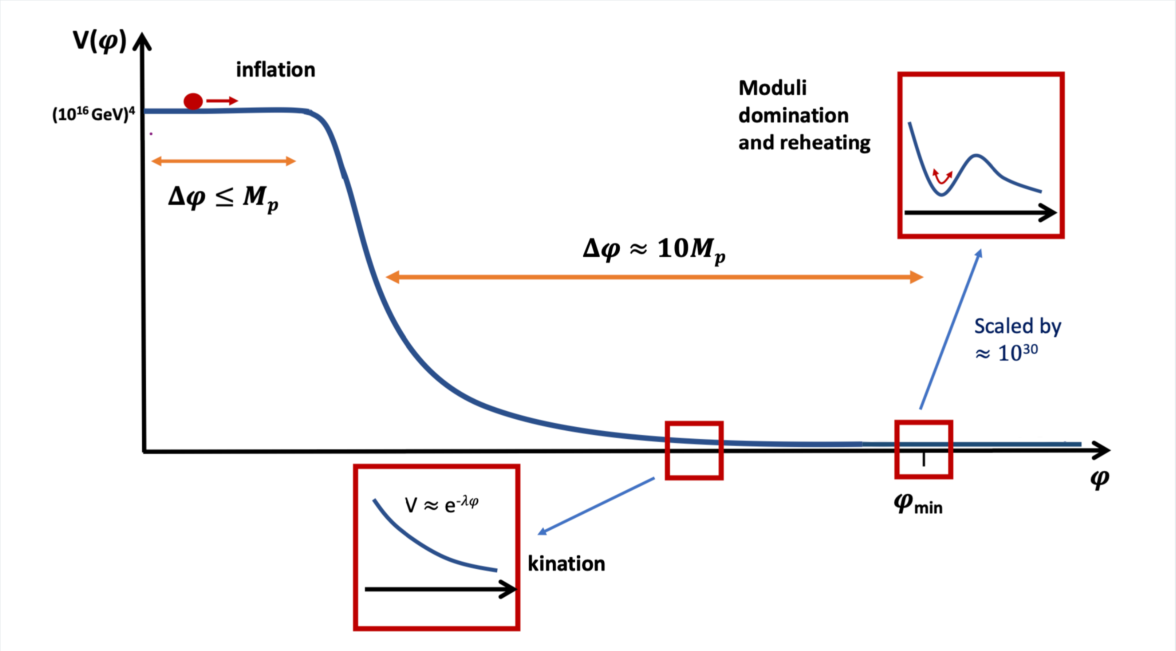
Strings meet and form network

PERCOLATINGS SUPERSTRINGS

- Percolation ends once kination ends

  (a) background reaches tracker solution as radiation catches up with kination

  (b) kinating modulus settles down in its final minimum



- String networks enter a scaling regime $\rho_{strings,init} \sim \mu H^2$ and lose energy via emission of gravitational radiation

- Final tension has $\mu \sim m_s^2$ with $G\mu \sim \dfrac{m_s^2}{M_P^2} \sim 10^{-10}$ in for phenomenologically appealing vevs for volume.

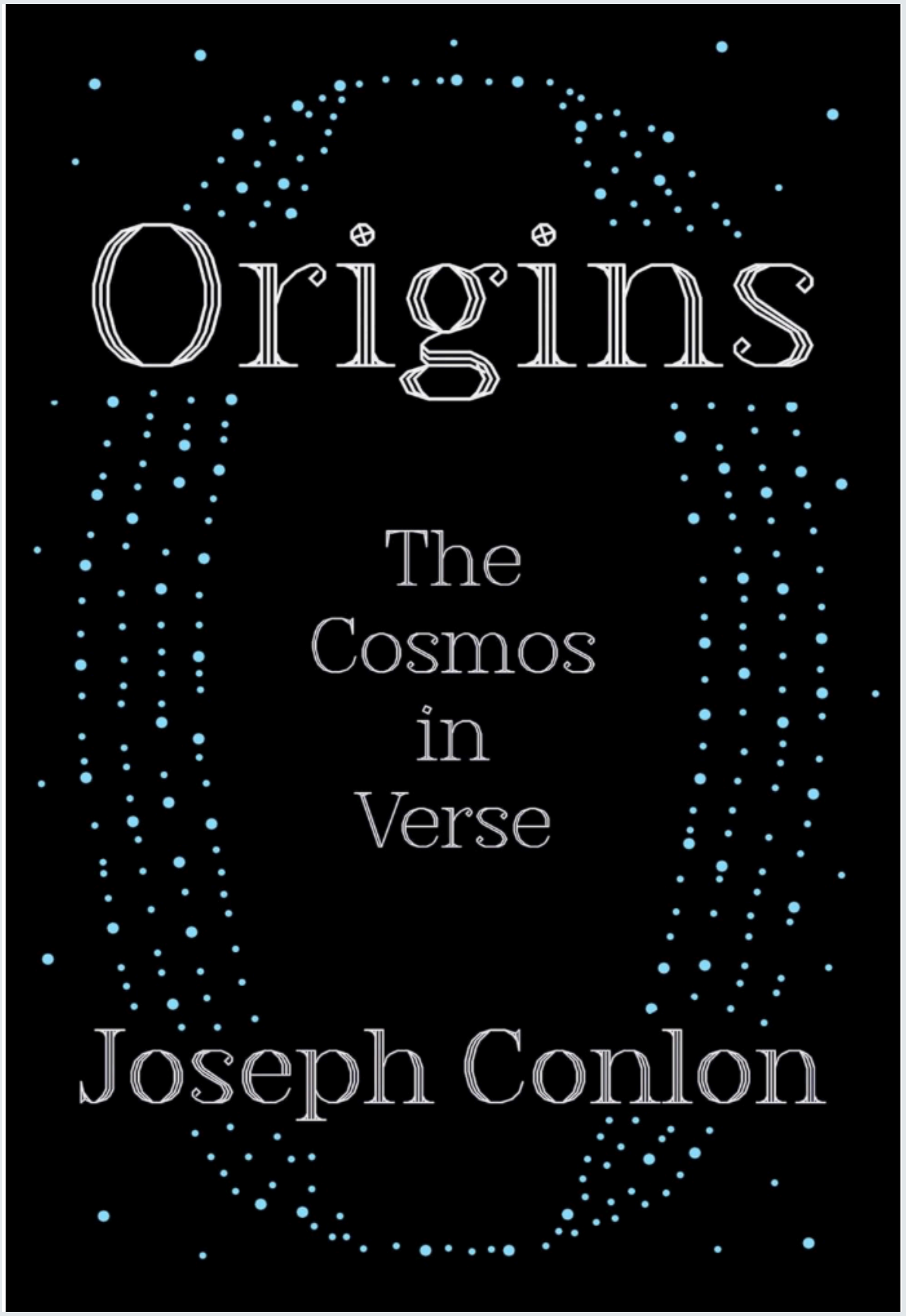
WILL NOT TALK ABOUT

- Conditions for overall stability of cosmic strings against immediate fragmentation (Copeland + Polchinski 2005)
- Initial conditions: we need a starting population of isolated small loops (from quantum nucleation? Brane inflation?)
- Gravitational wave emission from closed loops (see paper; too slow to affect loop growth)
- Numerical details of endpoint of percolation
- Effects of $2H + \frac{\dot{\mu}}{\mu} < 0$ and loop growth on any existing string network
-

CONCLUSIONS

- If *String Phenomenology* means understanding this universe, the boundaries of moduli space are natural places to live: contains interesting vacua (LVS, DGKT)
- Reaching such vacua involves long kination epochs
- During volume kination, fundamental string loops grow and can percolate to form a cosmic string network
- New mechanism (distinct from Kibble mechanism) to form string networks
- 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)

ADDENDUM: CHRISTMAS PRESENT



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