Cascading in the Early Universe

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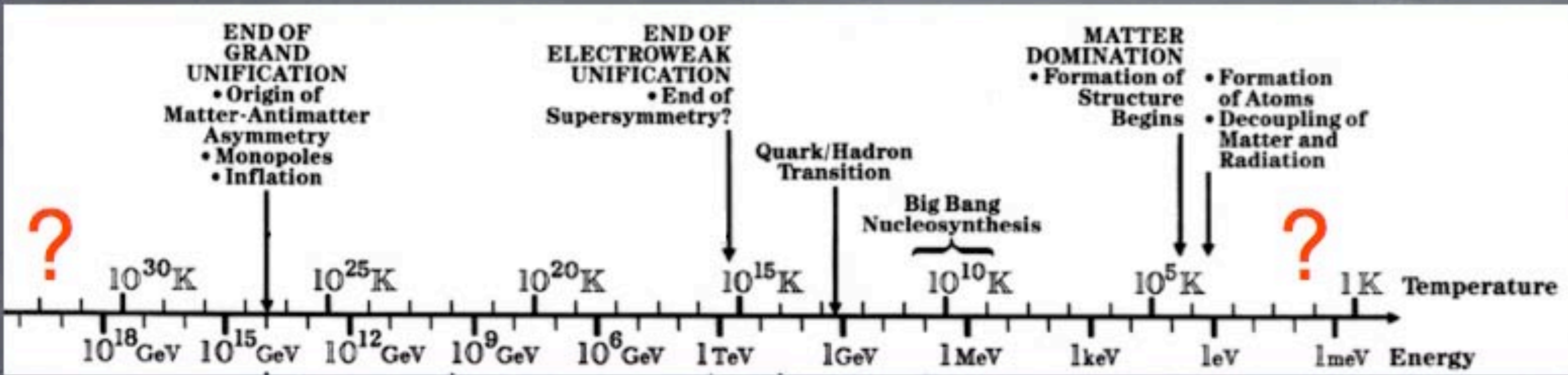
  Fred Adams, Sera Cremonini, Katie Freese, Chris Gauthier, Gordon Kane, Jim Liu
- Toronto / CITA:
  Lev Kofman

Overview

- Brief Review of Inflation Model Building
- Inflation in String theory -- and a problem...
- Moduli Trapping
- Transitions through the landscape
- Coarse graining and a multi-fluid approach to inflation
- Cosmological Perturbations
- Conclusions

Phase Transitions and Cosmology



Phase Transitions can result in many experimental signatures:

- Gravity Waves
  1st order: Bubble collisions, Turbulence
  2nd order: Inhomogeneous inflaton decay
- Density fluctuations
- Relic Abundances (e.g. neutrino background)
- Defect Formation (e.g. Cosmic strings, Domain walls)

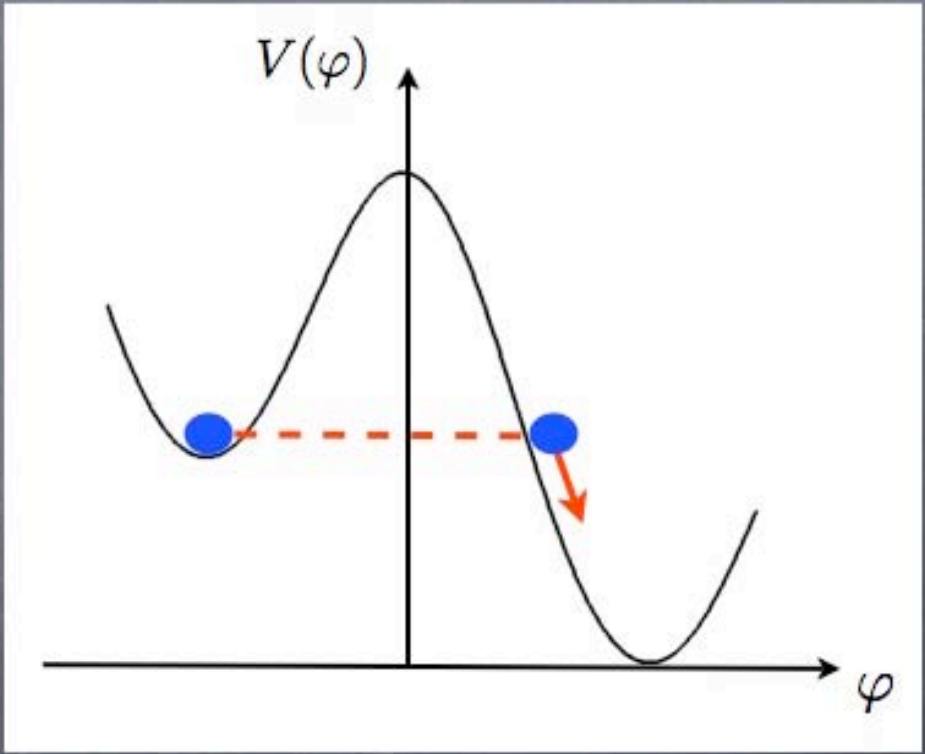
Vacuum Manifolds and Gauge Theories

- Gauge Theories can have rich vacuum structure
  (e.g. Theta vacuum)
- Non-perturbative behavior
  (e.g. Gaugino condensation, solitons, instantons)
- String theory Landscape
  Strings, Branes, lots of fluxes

Old Inflation

Guth and Weinberg, 1981
SU(5) GUT (well motivated by fundamental theory)

Could potentially solve:
- *Monopole problem*
- Horizon problem,
- Flatness problem,
- Entropy problem



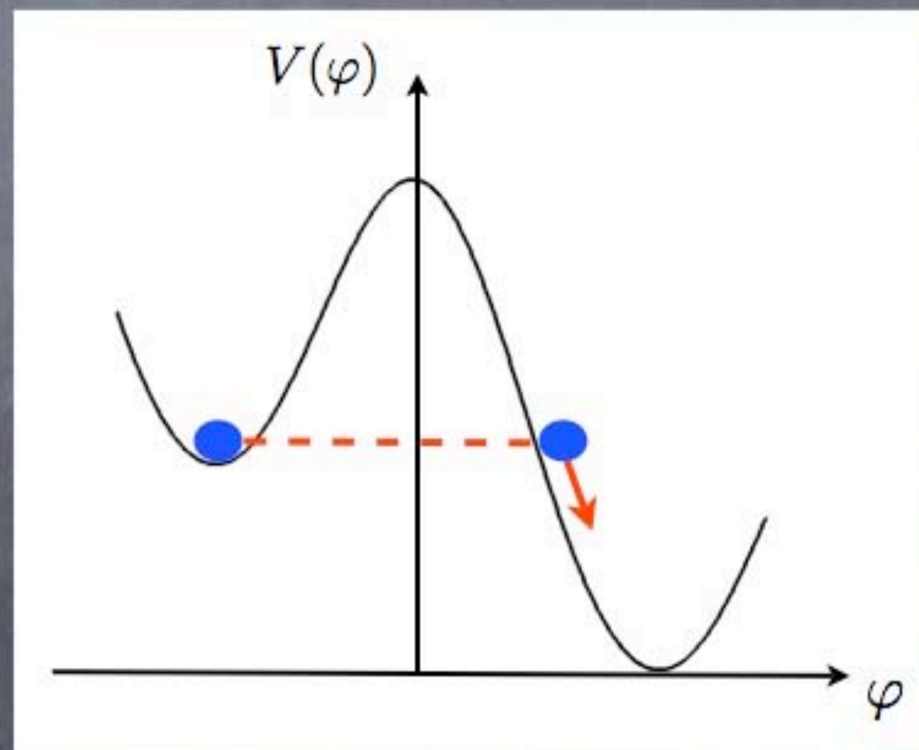
AND (accident)
gives explanation for origin of
Scale Invariant Spectrum of density perturbations (LSS)
(maybe some gravity waves too)

Old Inflation doesn't work

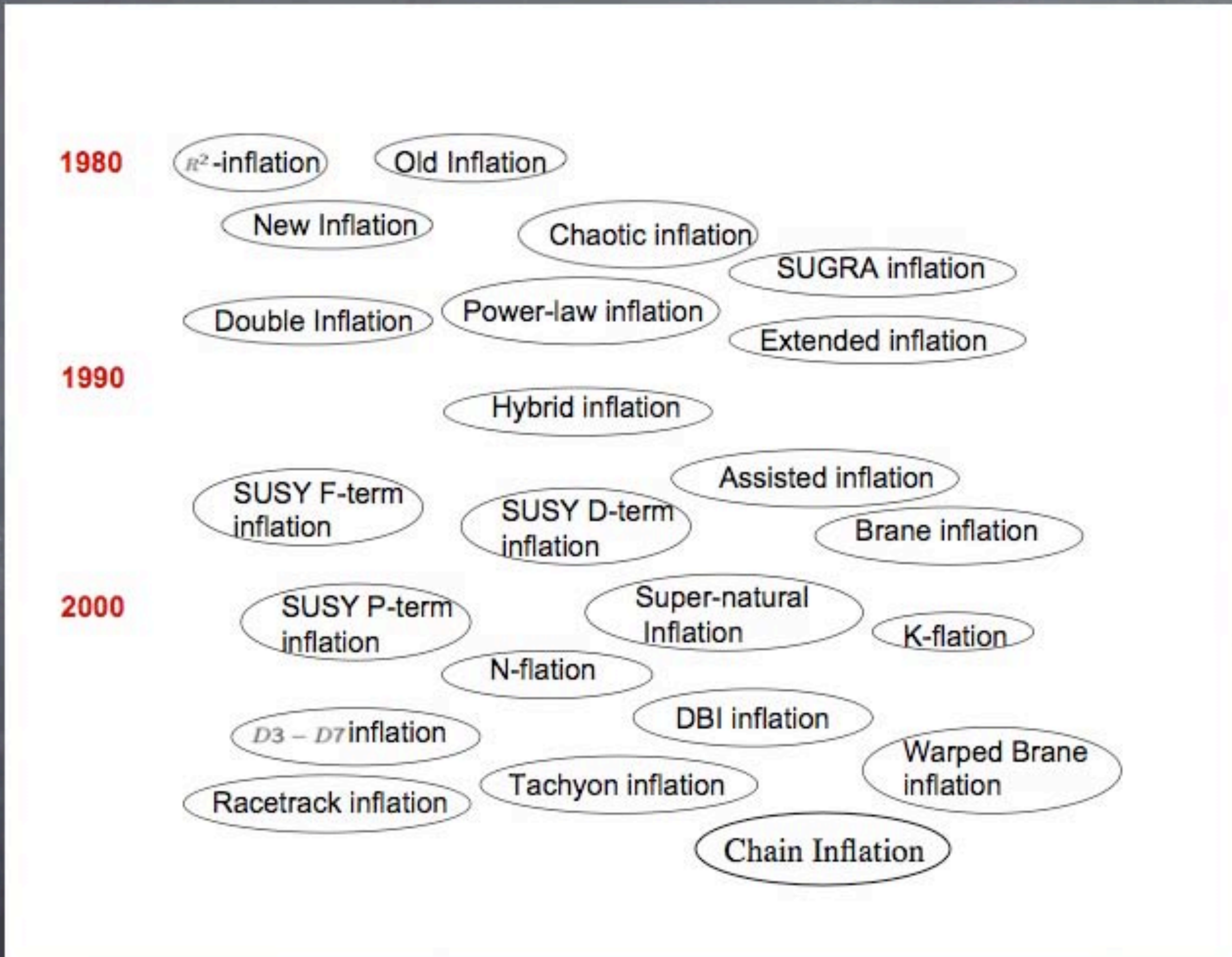
- 1st order transition – Single Tunneling Event
- Potential difference must yield enough inflation
- Bubbles of new phase must percolate

Unfortunately:

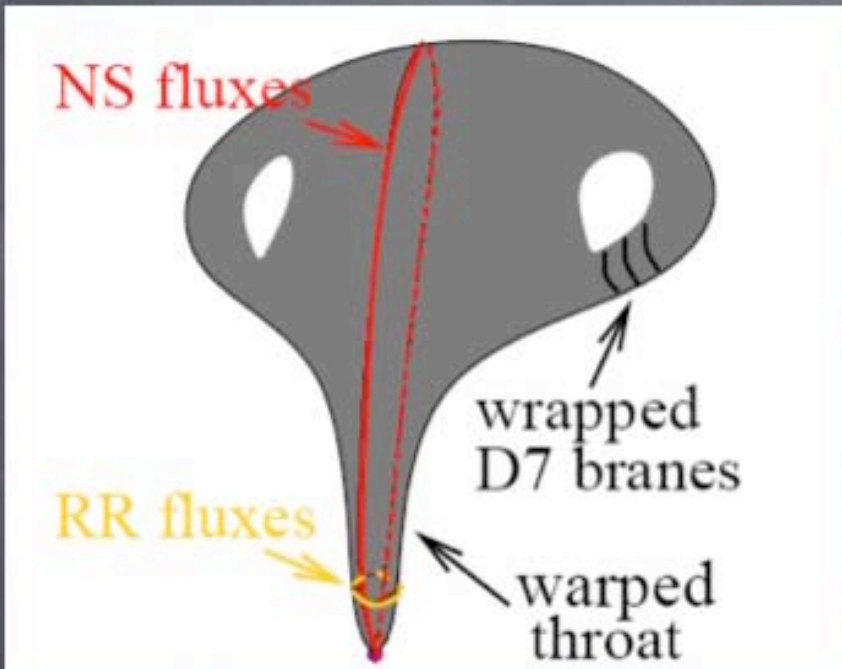
- Inflation doesn't end
(Graceful Exit Problem)
- Single universe emerges
- Can't reheat (cold & empty)



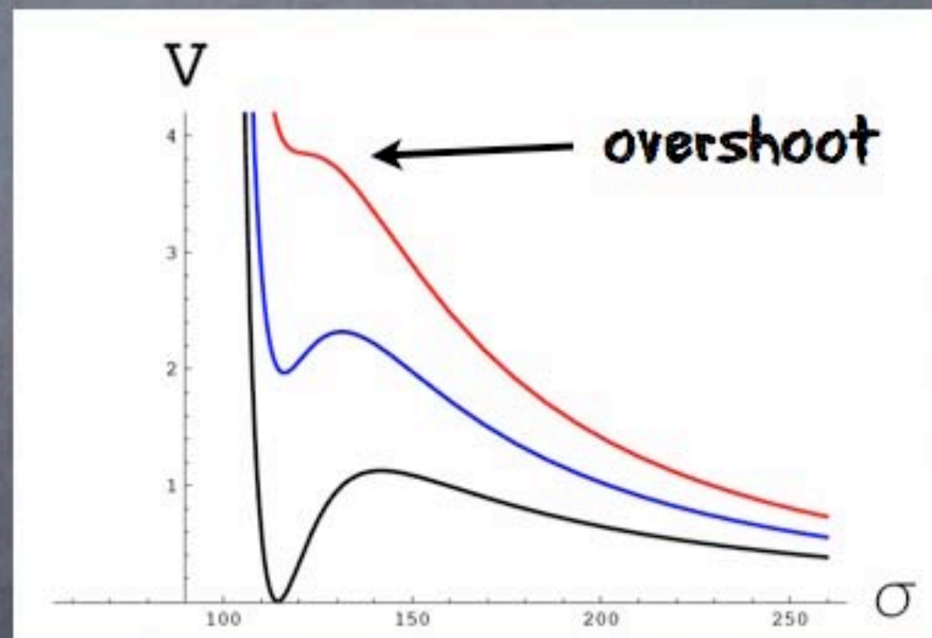
Inflation remains an idea w/out a theory (no UV completion)



Towards inflation in string theory (e.g., KKLT, KKMMLT, BBCEGKLQ, etc..)



Universe is hot
--> Finite Temp.



Many moduli - flat directions to stabilize

Is Symmetry Attractive?

Are all minima equal?

Review of Strings on S^1

SUGRA Massless modes:

$R \equiv \sqrt{G_{55}} \rightarrow \phi \qquad A_\mu^{R/L} = G_{\mu 5} \pm B_{\mu 5} \qquad$ Chiral $U(1)$

Higgsed scalar w/ winding charge (w/ knowledge of string theory)

$m_w^2 = m_s^2(\omega^2 R^2 - 4) \qquad w = \pm 2$

Time dependent effective mass

$m_w^2 = g^2 \phi^2(t)$

Enhanced gauge symmetry - ESP @ self-dual radius

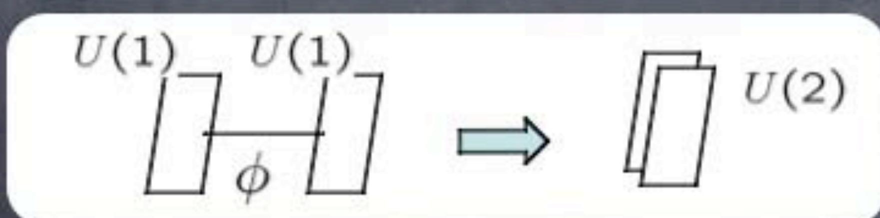
$R \rightarrow l_s \qquad m_w \rightarrow 0 \qquad U(1) \rightarrow SU(2)$

8 new scalars
4 new vectors

Enhanced Symmetry

Many examples of ESPs in string theory

- Heterotic strings on T^6 – Enhanced gauge symmetry
- Type II on K3 – ESPs at singularities
- Wrapped branes and strings on collapsing cycles (e.g. conifolds and flops)
- Coincident branes (open strings become light)



Moduli Trapping

- Kofman, Linde, Liu, Maloney, McAllister, Silverstein hep-th/0403001
- S.W. hep-th/0404177
- Cremonini & S.W. hep-th/0601082
- Greene, Judes, Levin, Weltman, & S.W. - to appear soon

$$\ddot{\phi} + 3H\dot{\phi} + g^2\langle\chi^2\rangle\phi = 0$$

$$\ddot{\chi} + 3H\dot{\chi} + g^2\langle\phi^2\rangle\chi = 0$$

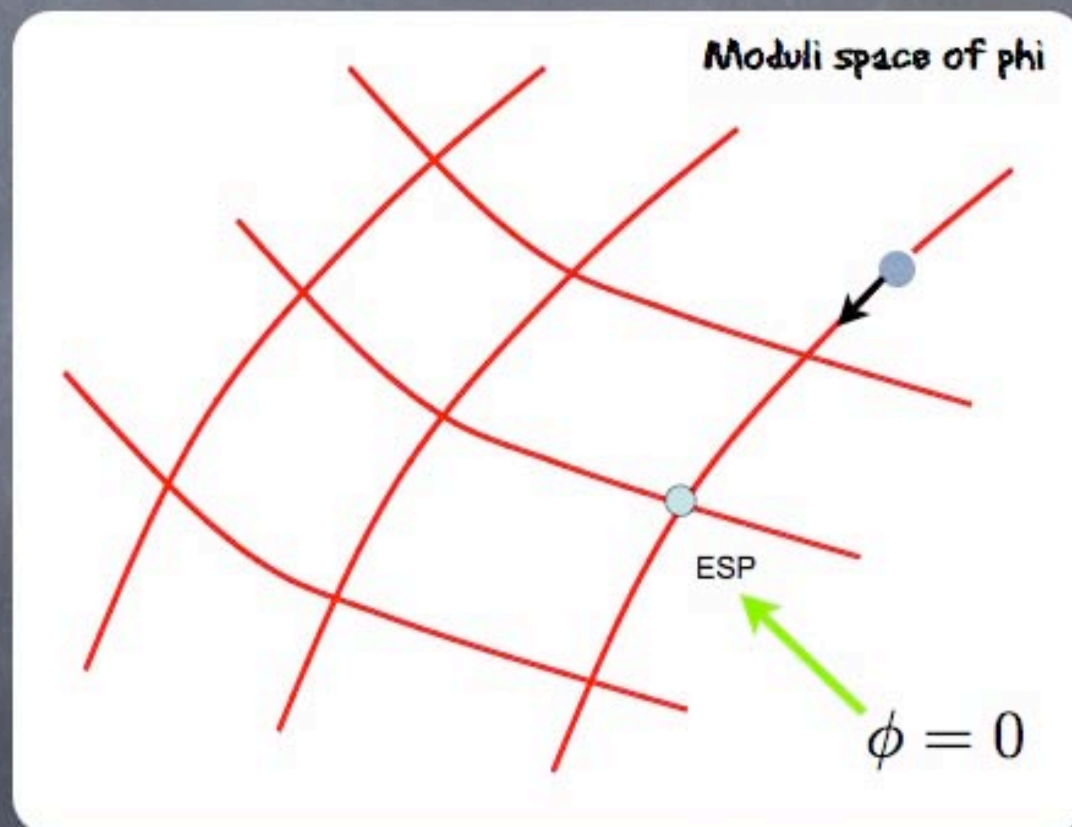
Initially: $\langle\chi^2\rangle = 0$

Adiabaticity parameter

$$\frac{\dot{\omega}}{\omega^2} \approx \frac{\dot{m}}{m^2} \sim 1$$

Near ESP modes become excited

-Particle production-



$$\ddot{\phi} + 3H\dot{\phi} + g^2\langle\chi^2\rangle\phi = 0$$

Initially: $\langle\chi^2\rangle = 0$

Adiabaticity parameter

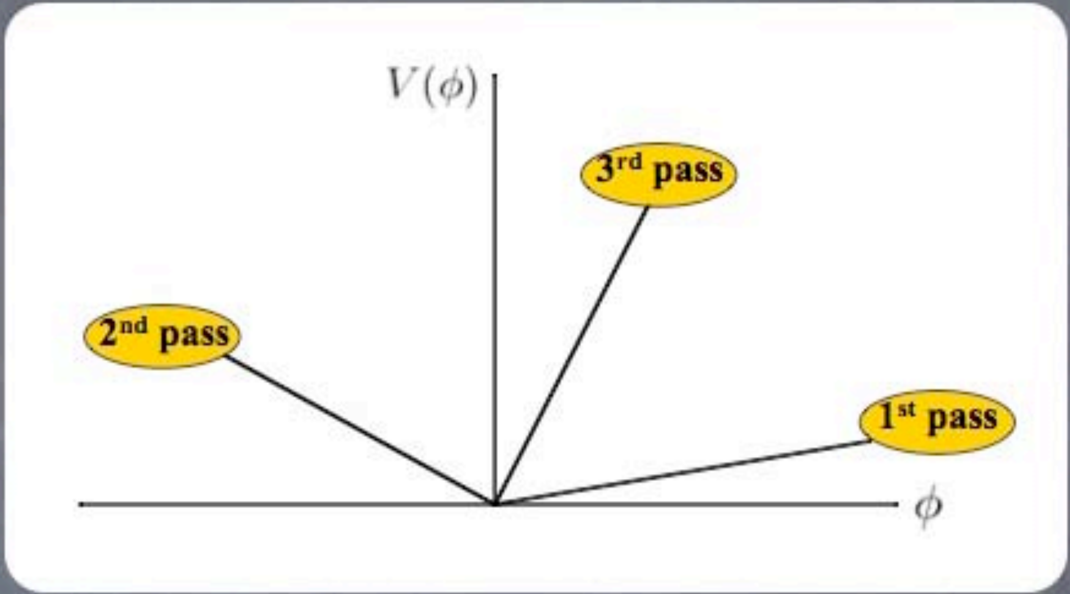
$$\frac{\dot{\omega}}{\omega^2} \approx \frac{\dot{m}}{m^2} \sim 1$$

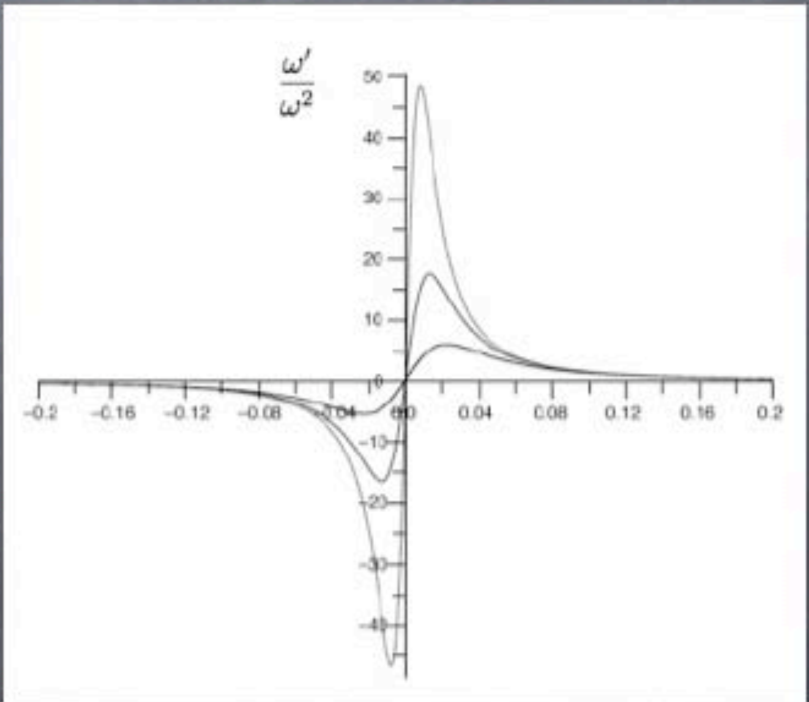
Near ESP modes become excited

-Particle production-

$$n_k \approx e^{-\frac{\pi k^2}{g v_0}}$$

$$\ddot{\phi} + 3H\dot{\phi} = -g n_\chi \frac{\phi}{|\phi|}$$

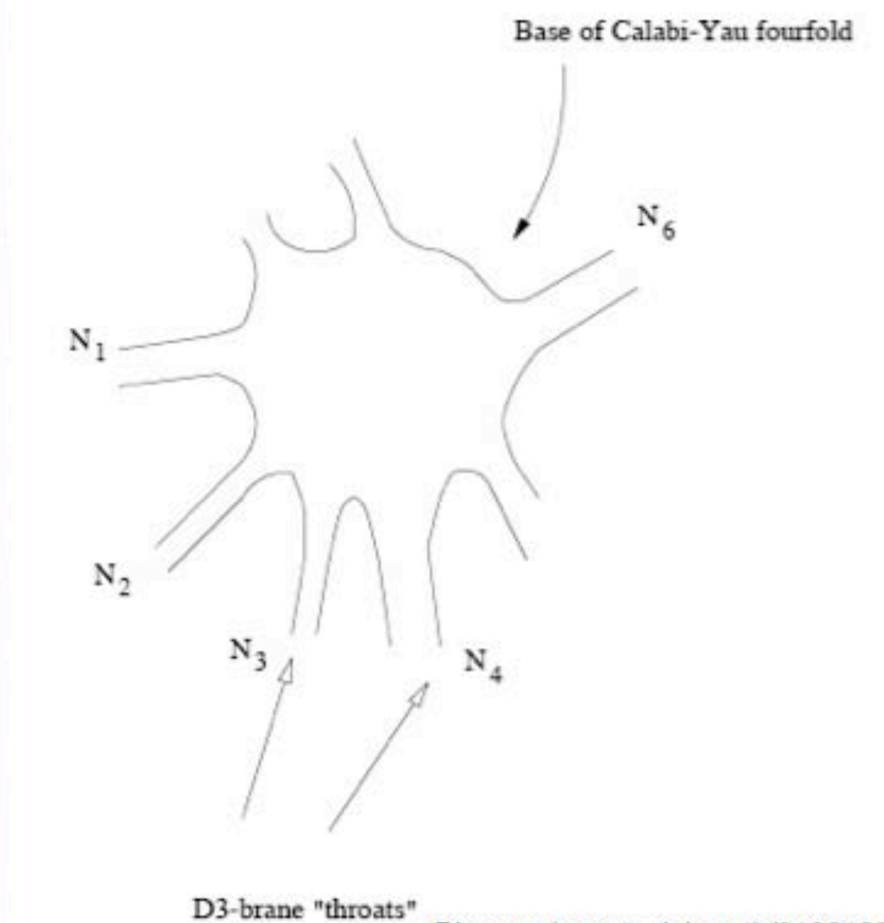




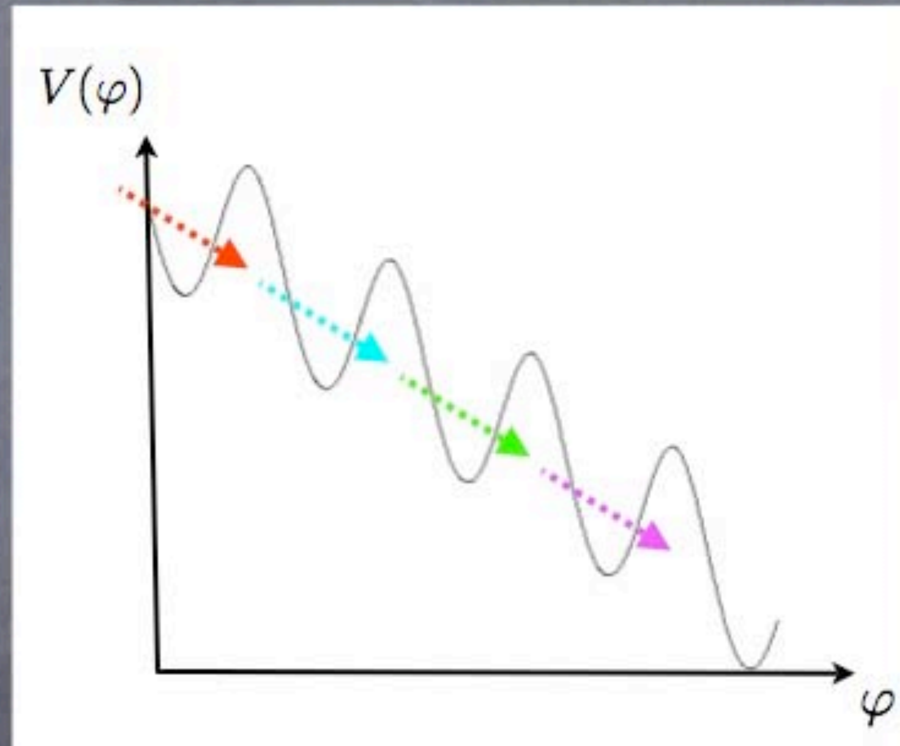
"Observations"

- Moduli dynamics require careful study of moduli space - new light d.o.f. (c.f. Vafa - Swampland)
- Points of enhanced symmetry seem to be dynamical attractors - some pts. in landscape preferred dynamically
- ESPs are fixed pts. of effective action... even after phase transition (protected by symmetry - c. f. Dine)
- Fixed points of dualities natural places to find moduli
- Can moduli dynamics + gravity generate hierarchies?
- The dilaton - difficult - but possible
  (Cremonini & S.W. hep-th/0601082)

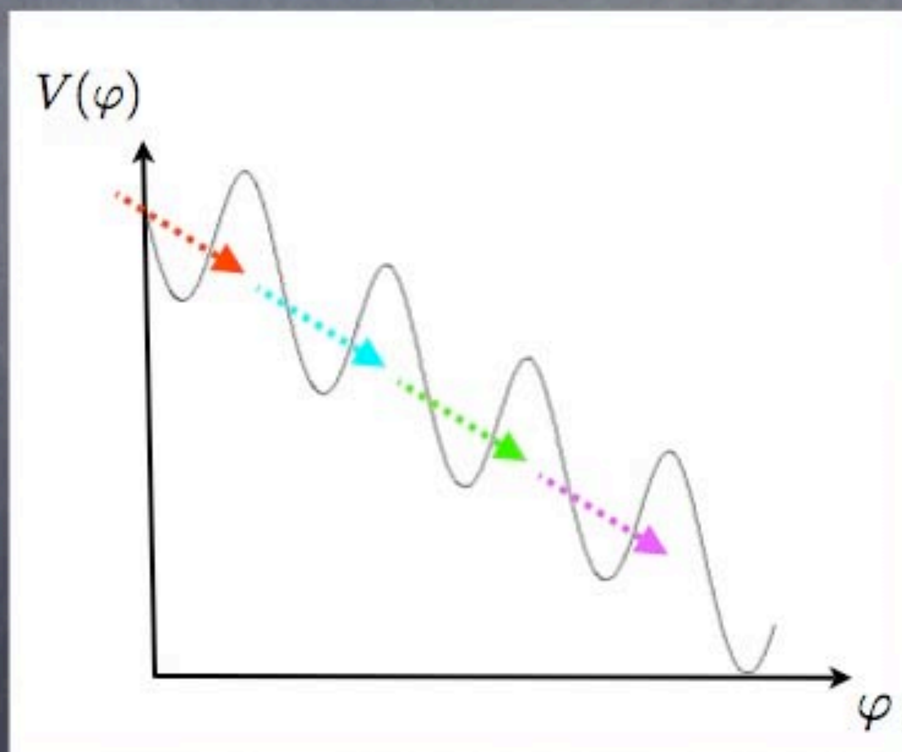
Traveling through the landscape



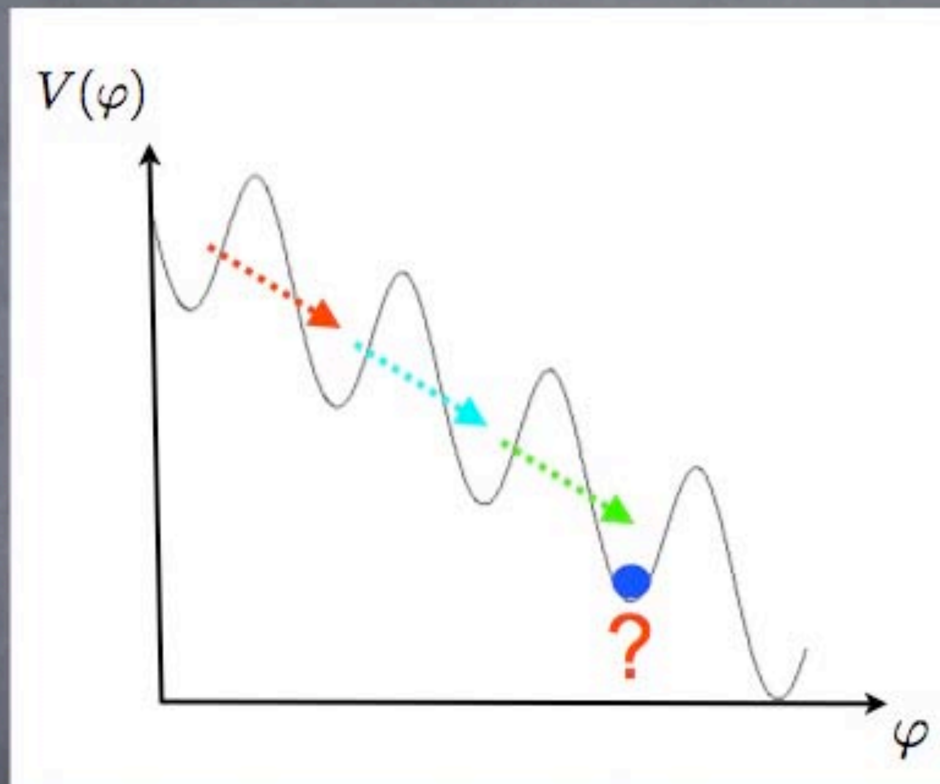
Dimopoulos, et. al, hep-th/0106128



- Did the universe go through a series of rapid phase transitions?
- 1st or 2nd order?
- Can a successful model of inflation result?
- Signatures?



- Can this address the Cosmological constant problem? (Abbott)



Traveling through the landscape

Bousso-Polchinski (extension of Brown-Teitelboim mechanism)

$$F^{(i)}_{\mu\nu\rho\sigma} = n_i q_i \epsilon_{\mu\nu\rho\sigma} \qquad n \in \mathbb{Z}$$

$$\Lambda = \Lambda_{\rm bare} + \sum_{fluxes} \frac{1}{2} n_i^2 q_i^2$$

Make Λ dynamical: $\Lambda \longrightarrow F_{(4)}$

Membrane nucleation (instantons)

$$n \to n-1$$

Energy drop

$$\epsilon^4 = -\left(n - \frac{1}{2}\right) q^2$$

Ex: M-theory compactification

$$\tau_4 = 2\pi M_{11}^3 (V_3 M_{11}^3)$$ M5 --> 4D

$$M_{11} \sim 10^{-3} M_p$$

$$V_3 M_{11}^3 \sim 10^3 \qquad n \sim 1000$$

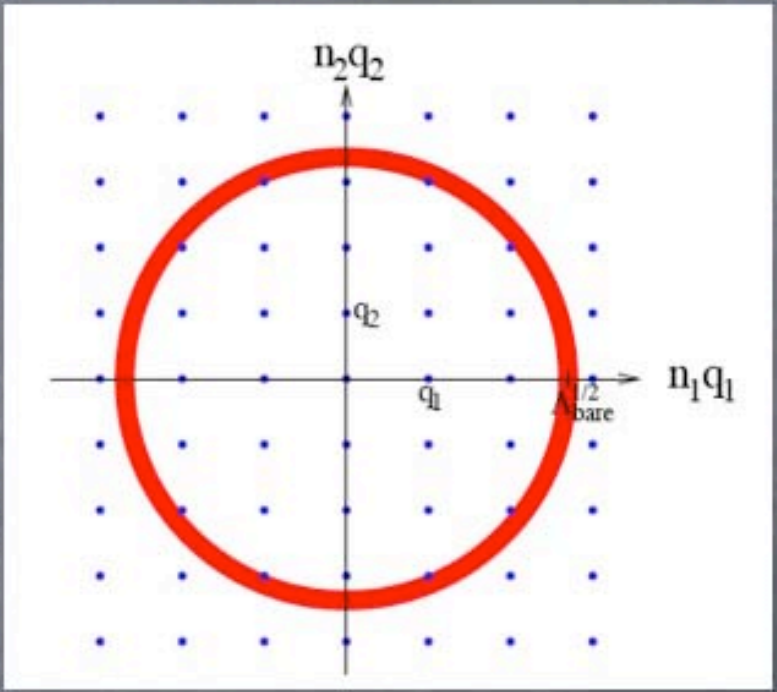
$$\epsilon^4 \sim 10^{-7} M_p^4$$

Can we use degeneracy of vacua to address naturalness?

Kane, Perry, and Zytkow, hep-th/0311152

Near degeneracy

--> Super-position of vacua



Ground State Energy

$$\rho(\theta) \approx H^2 M_p^2 - 2\sum_{i=1}^{d} H^4 cos(\theta_i) e^{-S_E}$$

$$H \sim 10^{15} GeV$$

$$d \sim 10^{12} \quad N \sim 10^{100}$$

$$\longrightarrow \quad \rho_0 \sim \left(10^{-3} eV\right)^4$$

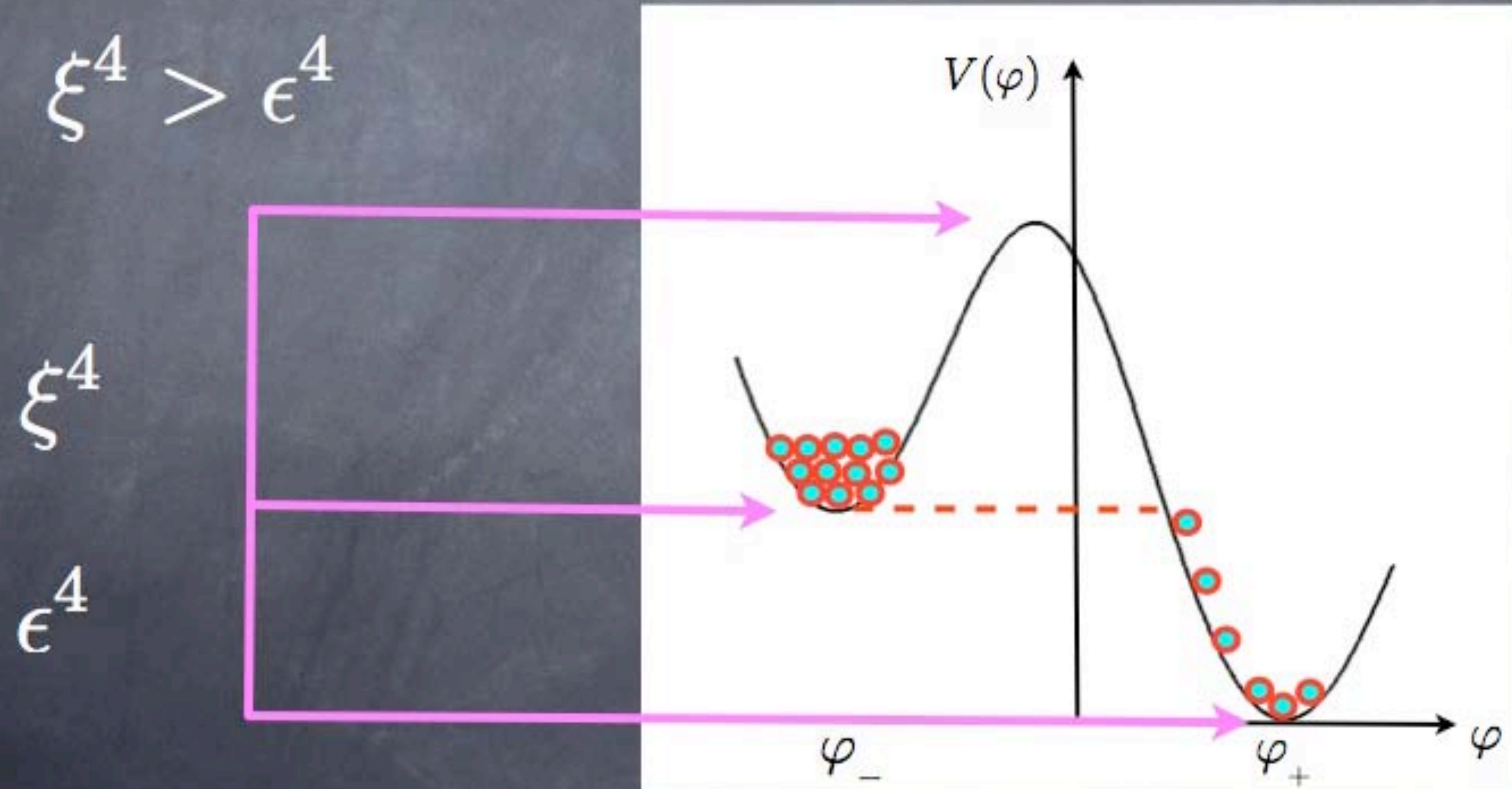
Early Universe would have band structure --> interesting cosmology

S.W., Kane, Perry, and Adams, hep-th/06010054

First Order Transitions

- Bubbles of new phase form in background of old phase
- Energy difference stored in walls / velocity typically relativistic
- Bubble collisions create regions of new phase as they collide
- Transition completes when all bubbles collide (percolation) and bath of radiation results

$$\xi^4 > \epsilon^4$$

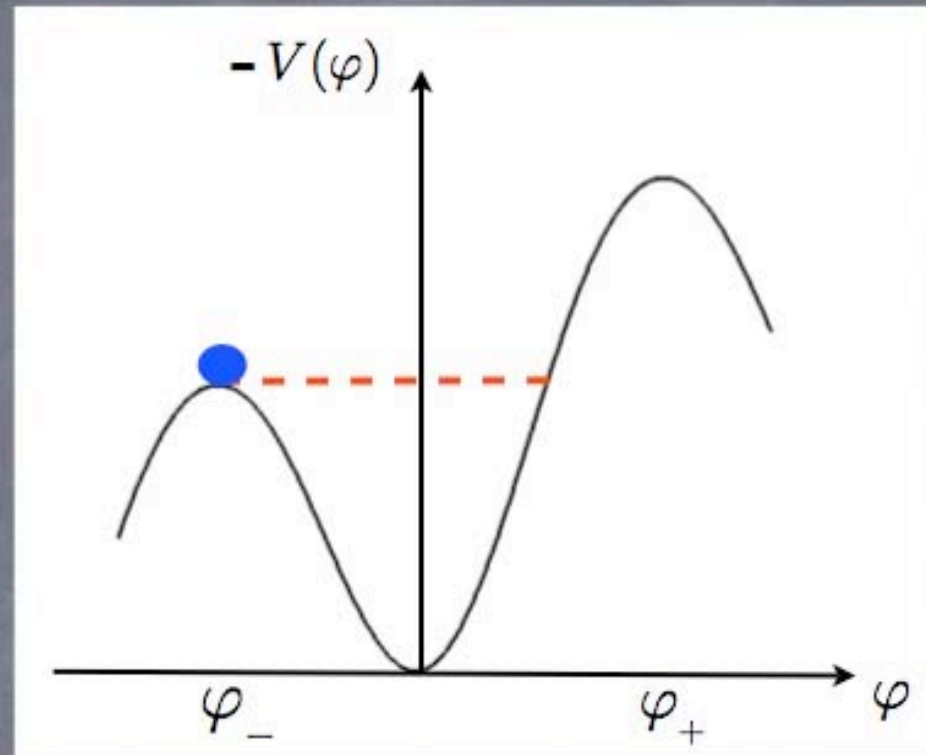


The Bounce

$$\Gamma = Ae^{-B} \qquad A \sim \epsilon^4$$

$$\epsilon^4 = V(\varphi_+) - V(\varphi_-)$$

$$B = S_E(\varphi_b) - S_E(\varphi_-)$$



Dimensionless Decay rate

$$\beta = \frac{\Gamma}{H^4}$$

Percolation and e-folds

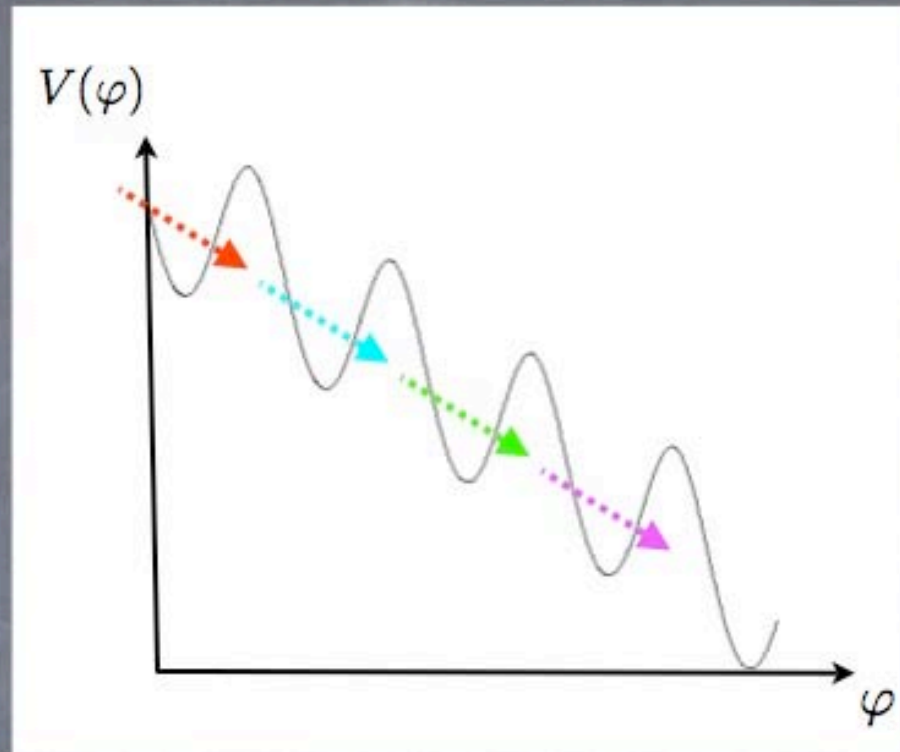
$$p(t) \sim e^{-\frac{4\pi}{3}\beta H t} \qquad \tau \sim (\beta H)^{-1}$$

$\beta \geq \frac{9}{4\pi}$ graceful exit $\longrightarrow$

$$N = \int H dt \approx H\tau \leq \frac{1}{3}$$

$\beta \ll 1$ enough e-folds

$$N = \int H dt \approx H\tau \leq \frac{1}{3}$$



Observations:

- Transitions will be weakly first order
- Characteristic bubble size << Hubble scale

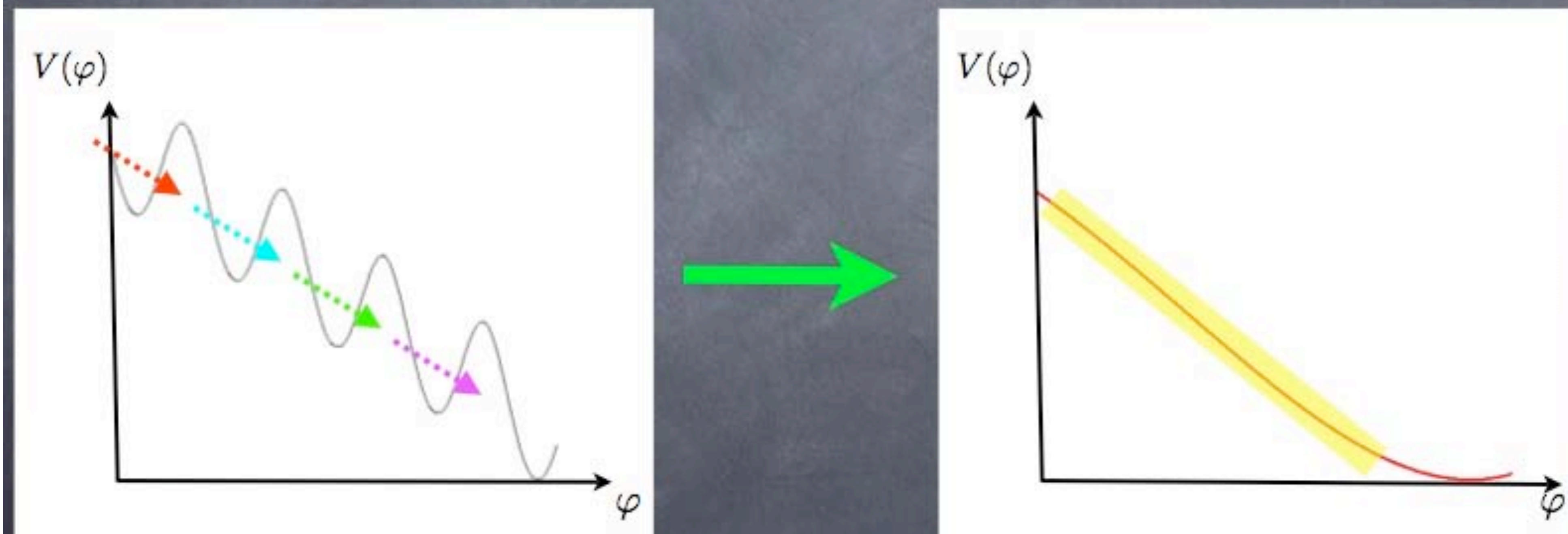
(gravitational effects unimportant)

$$r_b \ll H^{-1} \qquad r_b \sim \frac{\xi^2 \Delta\varphi}{\epsilon^4}$$

Hawking, Moss, and Stewart Phys Rev D26 1982

Macroscopic description

- Coarse grain --> Bubbles act as radiation bath $r_b \ll H^{-1}$
- Slow roll inflation w/ radiation present



Cosmology with Multiple Fluids

$$\nabla_\mu T^{\mu\nu}_{(\alpha)} = Q_{(\alpha)}$$

$$\nabla_\mu T^{\mu\nu}_{\text{total}} = 0 \qquad \sum_\alpha Q_{(\alpha)} = 0$$

$$\dot{\rho}_\varphi = -3H\dot{\varphi}^2 + Q_\varphi$$

$$\dot{\rho}_r = -4H\rho_r + Q_r$$

$$Q_\varphi = -Q_r$$

$$3H^2 = \frac{8\pi}{M_p^2}\rho$$

$$\dot{H} = -\frac{4\pi}{M_p^2}\left(\dot{\varphi}^2 + \frac{4}{3}\rho_r\right)$$

Inflation with Multiple Fluids

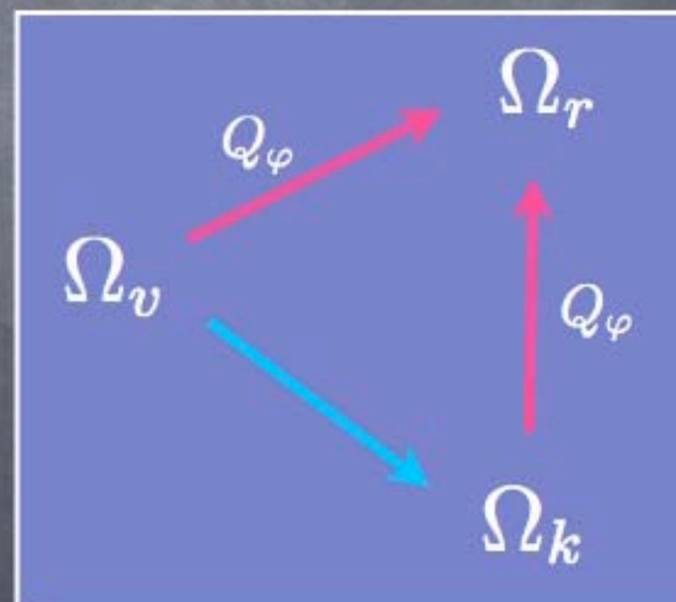
Standard slow roll inflation

$$\epsilon = \frac{d}{dt}\left(H^{-1}\right) = 3\Omega_k + 2\Omega_r$$

Effect of Bubbles

$$\Omega_k = \frac{\frac{1}{2}\dot{\varphi}^2}{\rho} \quad \Omega_r = \frac{\rho_r}{\rho} \quad \Omega_v = \frac{V(\varphi)}{\rho} \qquad \Omega_k + \Omega_v + \Omega_r = 1$$

$$\ddot{a} > 0 \longrightarrow \epsilon < 1$$



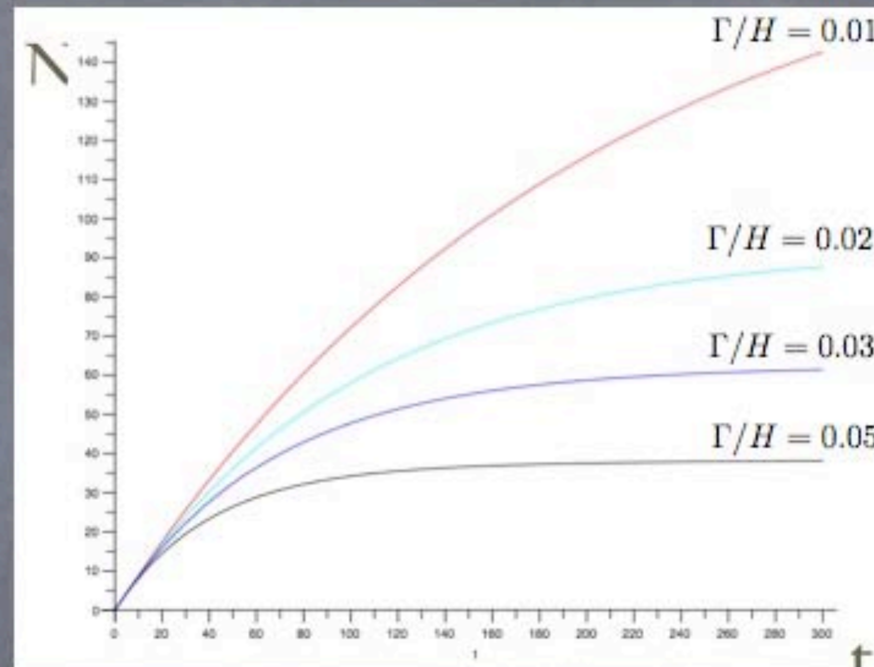
Example One: Inflation w/out inflatons

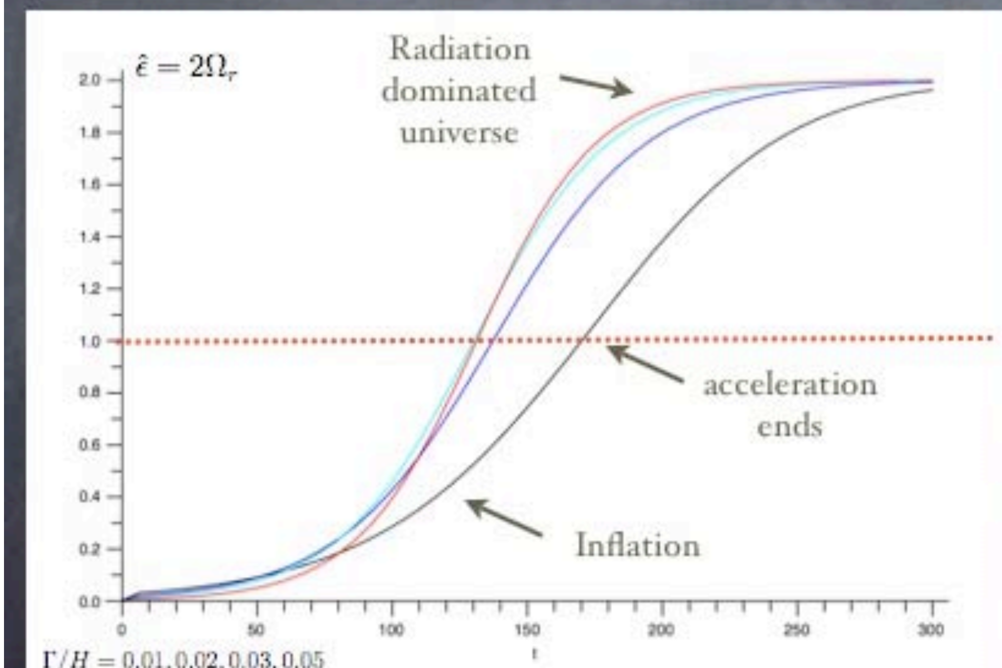
S.W., Perry, Kane, Adams hep-th/0610054

$$Q_\varphi = -\Gamma \rho_\phi \qquad \dot{\varphi} = 0$$

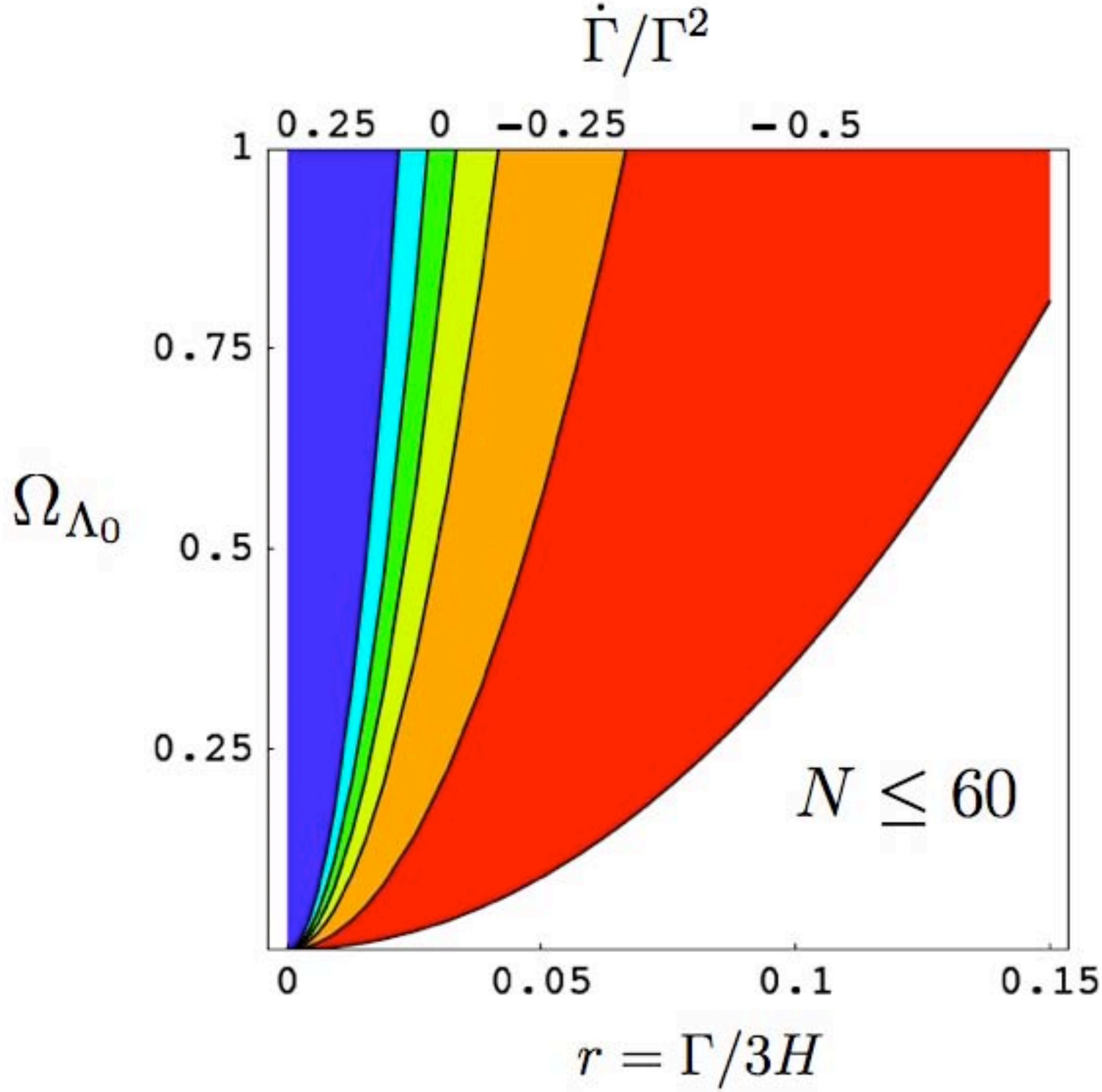
$$\dot{\rho}_\Lambda = -\Gamma \rho_\Lambda$$

$$\dot{\rho}_r = -4H\rho_r + \Gamma \rho_\Lambda$$





$$r = \frac{\Gamma}{3H} \lesssim \frac{1}{150}$$



$\dot{\Gamma}/\Gamma^2$
0.25
0
-0.25
-0.5
1
0.75
0.5
0.25
Ω_{Λ_0}
$N \leq 60$
0
0.05
0.1
0.15
$r = \Gamma/3H$

Example Two: Warm Inflation

Berera, astro-ph/9509049. Criticism: Linde & Yokoyama hep-ph/9809409

$$Q_\varphi = -\Gamma\dot{\varphi}^2$$

$$\dot{\rho}_r = -4H\rho_r + \Gamma\dot{\varphi}^2$$

$$\dot{\rho}_\varphi = -3H\dot{\varphi}^2 - \Gamma\dot{\varphi}^2$$

Condition for inflation

$$\epsilon = \epsilon_\varphi(1+r) \ll 1$$

Three regimes

$$r = \frac{\Gamma}{3H} \gg 1$$ Warm Inflation

$$r = \frac{\Gamma}{3H} \approx 1$$ New regime (motivated by bubbles)

$$r = \frac{\Gamma}{3H} \ll 1$$ Standard inflation

Comments about Warm Inflation:

- Reheating is not necessary
- Potential can be less fine-tuned if many vacua are present (e.g. string landscape)
- Thermal correction to inflaton potential can be important (place for concern / fine tuning?)
- When vacuum energy ~ radiation density

--> interesting physics!

- Initial state is modified (transplanckian effects? hep-th/0611277)

Density Perturbations

Scalar Metric Perturbations

(no anisotropic stress / longitudinal gauge / 1 d.o.f.)

$$ds^2 = -(1+2\Psi)\,dt^2 + a^2(1-2\Psi)\,d\vec{x}^2$$

Curvature Fluctuation

$$\zeta = -\Psi - \frac{H}{\dot{\rho}}\delta\rho \qquad\qquad \zeta_\alpha = -\Psi - \frac{H}{\dot{\rho}_\alpha}\delta\rho_\alpha$$

Entropy or Isocurvature Fluctuation

$$S_{\alpha\beta} = 3(\zeta_\alpha - \zeta_\beta)$$

Ex: Baryon / Photons (Isocurvature)

$$\delta\rho = 0 \rightarrow \delta\rho_b = -\delta\rho_\gamma \qquad\qquad S_{b\gamma} = \frac{\delta\left(n_b/n_\gamma\right)}{n_b/n_\gamma}$$

Standard Scenario

Curvature Fluctuation

$$\zeta = -\Psi - \frac{H}{\dot{\rho}}\delta\rho$$

$$\dot{\zeta} = -\left(\frac{H}{\rho + p}\right)\delta P_{\rm NAD}$$

$$\delta P_{\rm int}^{(\alpha)} = \delta p^{(\alpha)} - c_\alpha^2 \delta\rho^{(\alpha)}$$

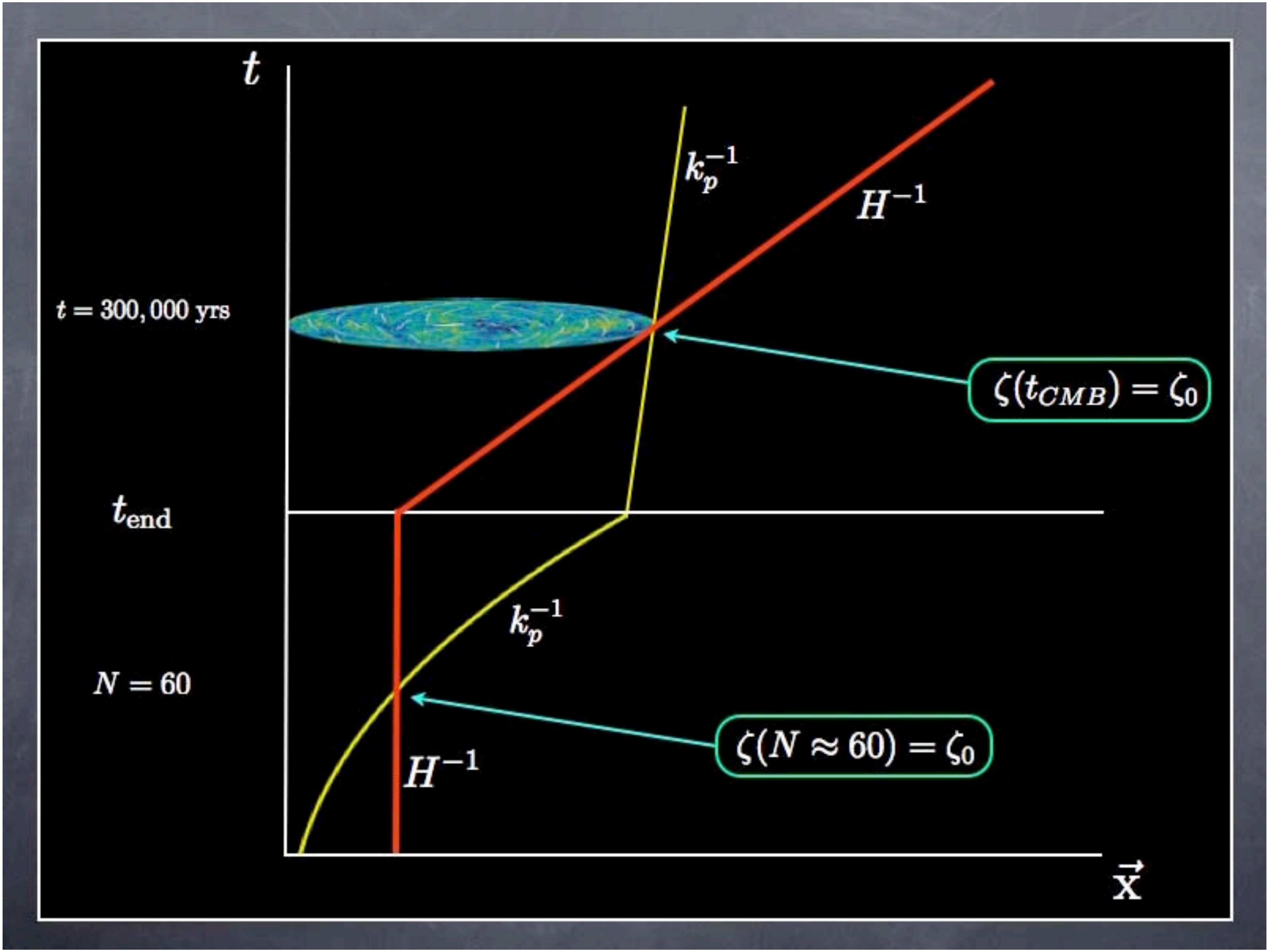
$$\delta P_{\rm rel} \sim \sum_{\alpha\beta} S_{\alpha\beta}$$

Scalar field inflation

$$\delta P_{\rm int}^{(\alpha)} \sim -k^2\Psi$$

$$\dot{\zeta} \to 0 \qquad k^{-1} \gg H^{-1}$$

Curvature perturbation conserved on Super-Hubble scales



t
k_p^{-1}
H^{-1}
$t = 300,000$ yrs
$\zeta(t_{CMB}) = \zeta_0$
$t_{\rm end}$
k_p^{-1}
$N = 60$
$\zeta(N \approx 60) = \zeta_0$
H^{-1}
$\vec{x}$

Density Fluctuations w/ multiple fluids (e.g. scalars)

$$\dot{\zeta} = -\left(\frac{H}{\rho + p}\right)\delta P_{\rm NAD}$$

Multiple fields w/ significant interactions can lead to new generation mechanisms:

- Perturbations during (p)reheating
- Curvaton
- Modulated Perturbations

Upshot: Significant contribution to density fluctuations can result *AFTER* inflation ends or by fields other than inflaton!

Modulated Perturbations

- Dvali Gruzinov, Zaldarriaga astro-ph/0303591 & astro-ph/0305548
- Kofman astro-ph/0303614 & astro-ph/0403315
- Kofman & S.W. – in progress

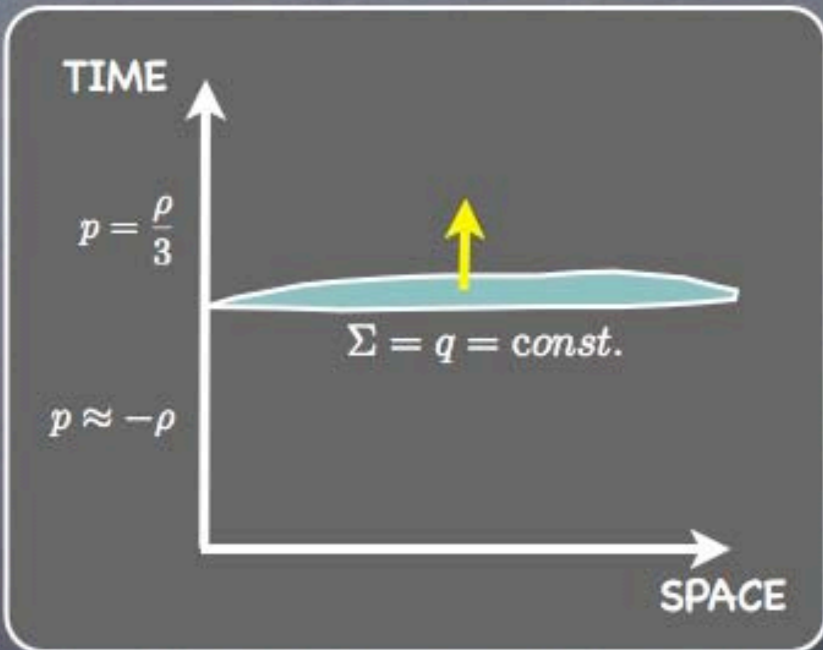
Light scalars during inflation

$$\delta\chi \sim \frac{H}{2\pi}$$

Couplings controlled by moduli will fluctuate

$$V(\phi) = \frac{1}{2}m^2(\chi)\phi^2 + \lambda^4(\chi)\phi^4$$

$$\frac{\delta\chi}{\chi} \rightarrow \left(\frac{\delta m}{m} \text{ or } \frac{\delta\lambda}{\lambda}\right) \rightarrow \frac{\delta\rho}{\rho} \rightarrow \frac{\delta T}{T}$$



Density Perturbations for Bubbles

Key Observations

$$r = \frac{\Gamma}{3H} \leq 1$$

$$\epsilon = 3\Omega_k + 2\Omega_r \ll 1$$

$$\rho_r \ll \rho_\varphi \rightarrow \delta\rho_r \ll \delta\rho_\varphi$$

Significant entropy perturbation can develop,
but radiation ultimately dominates washing out entropy perturbations
(c.f. Curvaton, Modulated Perrturbations)

Density Perturbations for Bubbles

$$\dot{\zeta} = -\frac{H}{\rho+p}\delta P_{\rm nad} + \frac{k^2}{3Ha^2}\left(\Psi-\zeta\right) + \frac{k^4}{9\dot{H}Ha^4}\Psi,$$

$$\dot{\Psi} = -\left(H - \frac{\dot{H}}{H}\right)\Psi - \frac{k^2}{3Ha^2}\Psi + \frac{\dot{H}}{H}\zeta,$$

$$\dot{\mathcal{V}_\phi} = -\left(\frac{Q_\phi(1+c_\phi^2)}{\dot{\phi}^2} - \frac{Q_\phi}{\dot{\phi}^2} - 3Hc_\phi^2 - \frac{2V'}{\dot{\phi}}\right)\mathcal{V}_\phi - \Psi + \frac{\dot{\rho}_\phi}{H\dot{\phi}^2}\left(\zeta_\phi + \Psi\right),$$

$$\dot{\zeta}_\phi = \frac{3H^2}{\dot{\rho}_\phi}\delta P_{\rm int}^\phi - \frac{H}{\dot{\rho}_\phi}\left(\delta\mathcal{Q}_{\rm int}^\phi + \delta\mathcal{Q}_{\rm rel}^\phi\right) + \frac{k^2}{3Ha^2}\left(\frac{Q_\phi}{\dot{\rho}_\phi}\Psi + \left[1 - \frac{Q_\phi}{\dot{\rho}_\phi}\right]H\mathcal{V}_\phi\right),$$

$$\delta P_{\rm nad} = \frac{2V'\dot{\phi}}{H}\left(\zeta_\phi + \Psi + H\mathcal{V}_\phi\right) + \frac{\dot{\rho}_\phi}{H}\left(c_r^2 - c_\phi^2\right)\left(\zeta - \zeta_\phi\right),$$

$$\delta P_{\rm int}^\phi = \frac{2V'\dot{\phi}}{H}\left(\zeta_\phi + \Psi + H\mathcal{V}_\phi\right),$$

$$\delta\mathcal{Q}_{\rm int}^\phi = \delta Q_\phi + \frac{\dot{Q}_\phi}{H}\left(\zeta_\phi + \Psi\right),$$

$$\delta\mathcal{Q}_{\rm rel}^\phi = \frac{Q_\phi\dot{\rho}}{2H\rho}\left(\zeta - \zeta_\phi\right),$$

Density Perturbations for Bubbles

Power Spectrum

$$P_\zeta = \frac{1}{4\pi^2 c_s \epsilon}\left(\frac{H}{M_p}\right)^2 (-k c_s \eta)^{-2\epsilon} \qquad \epsilon = 3\Omega_k + 2\Omega_r$$

Scalar Tilt:

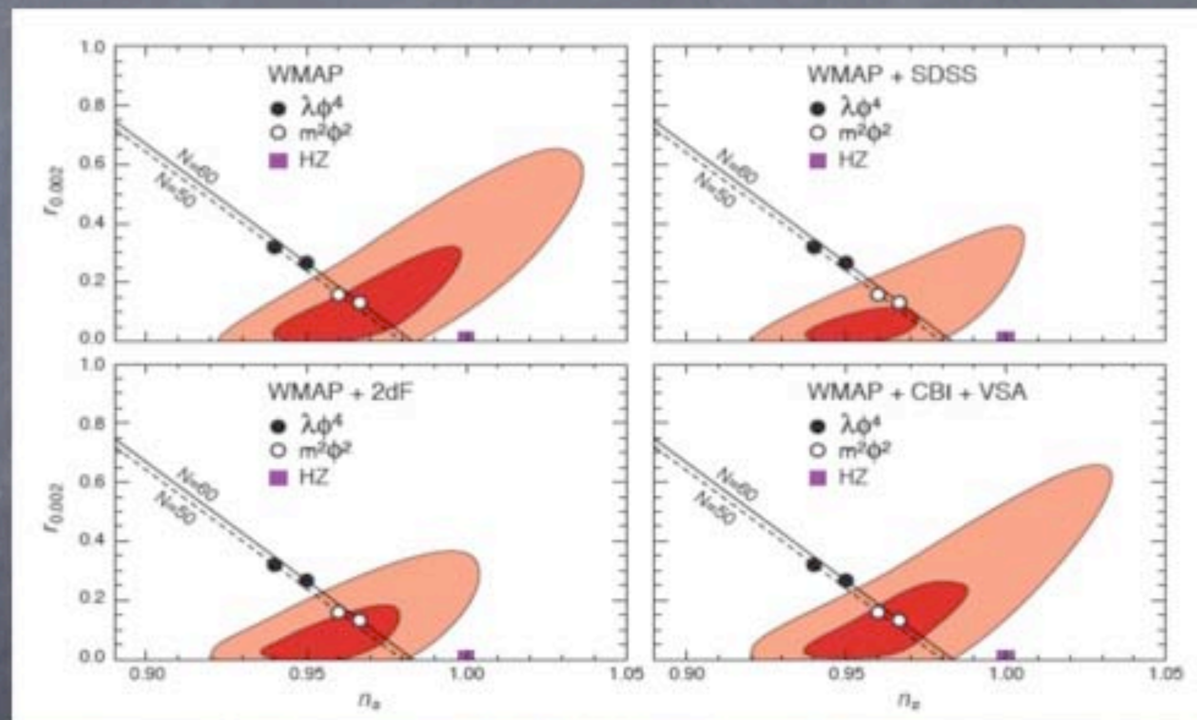
$$n_s = 1 + \frac{d\ln P_\zeta}{d\ln k} = 1 - 2\epsilon$$

Gravity Waves

$$P_h = \frac{8}{\pi^2}\left(\frac{H}{M_p}\right)^2 (-k\eta)^{-2\epsilon}$$

Tensor to Scalar ratio:

$$r = \frac{P_h}{P_\zeta} = 16\epsilon c_s$$



Single field slow-roll models

Conclusions

- Moduli Trapping offers a way to stabilize moduli near locations of higher symmetry
- Rapid transitions through landscape (1st or 2nd order) suggests new approach to fine tuning issues (replaced by energy splitting)
- Cosmological Perturbations are consistent with observations
- May be additional signatures.. gravity waves? tensor/scalar?
- Much left to explore...