VIABLE INFLATION MODELS WITH FIRST ORDER PHASE TRANSITION

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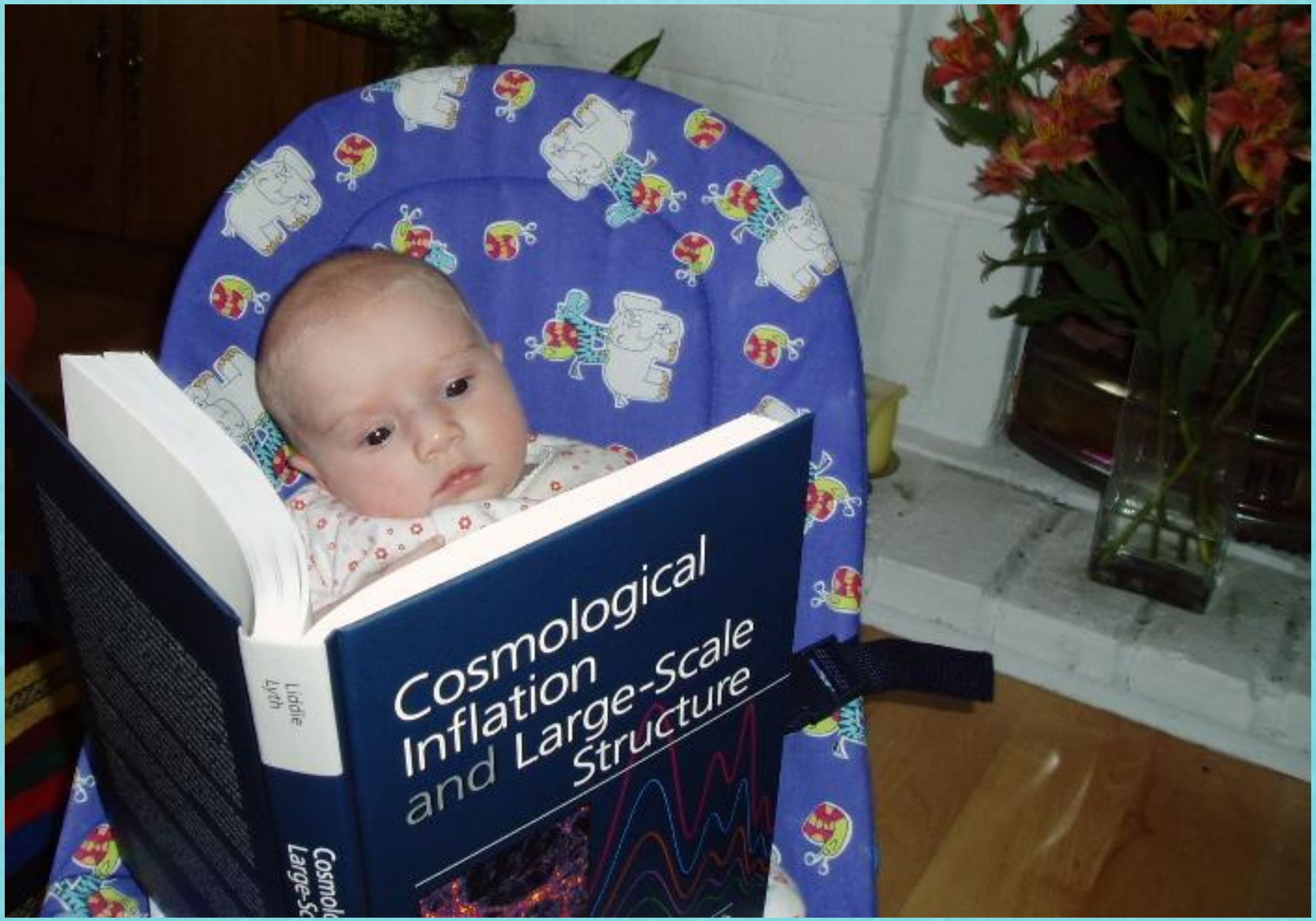
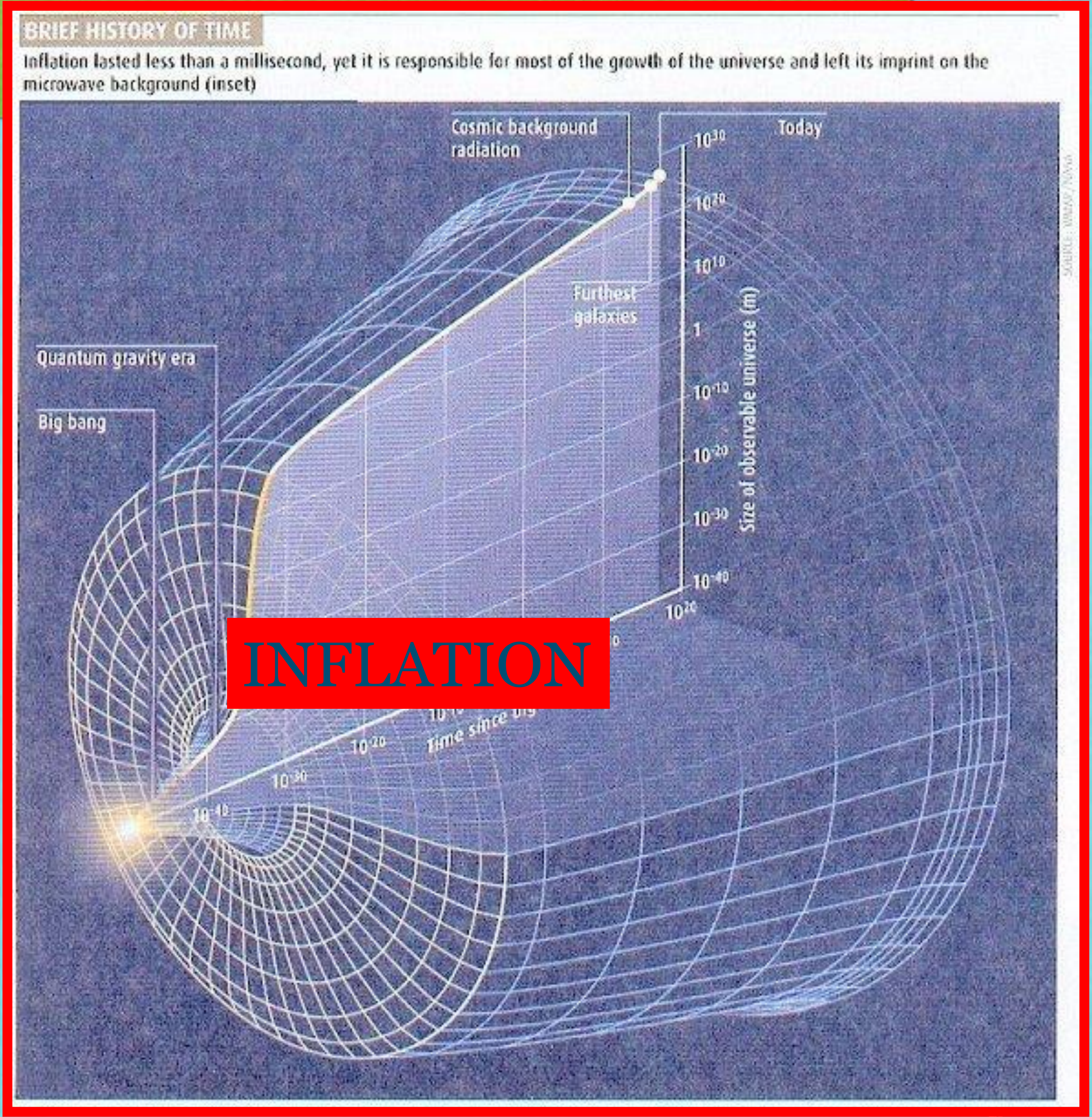
Inflation


Cosmological
Inflation
and Large-Scale
Structure
Liddle
Lyth

Inflation

- solves Big Bang theory problems
- wipes away all that came before
- sets the stage for structure to appear (gives inhomogeneities of the CMB)

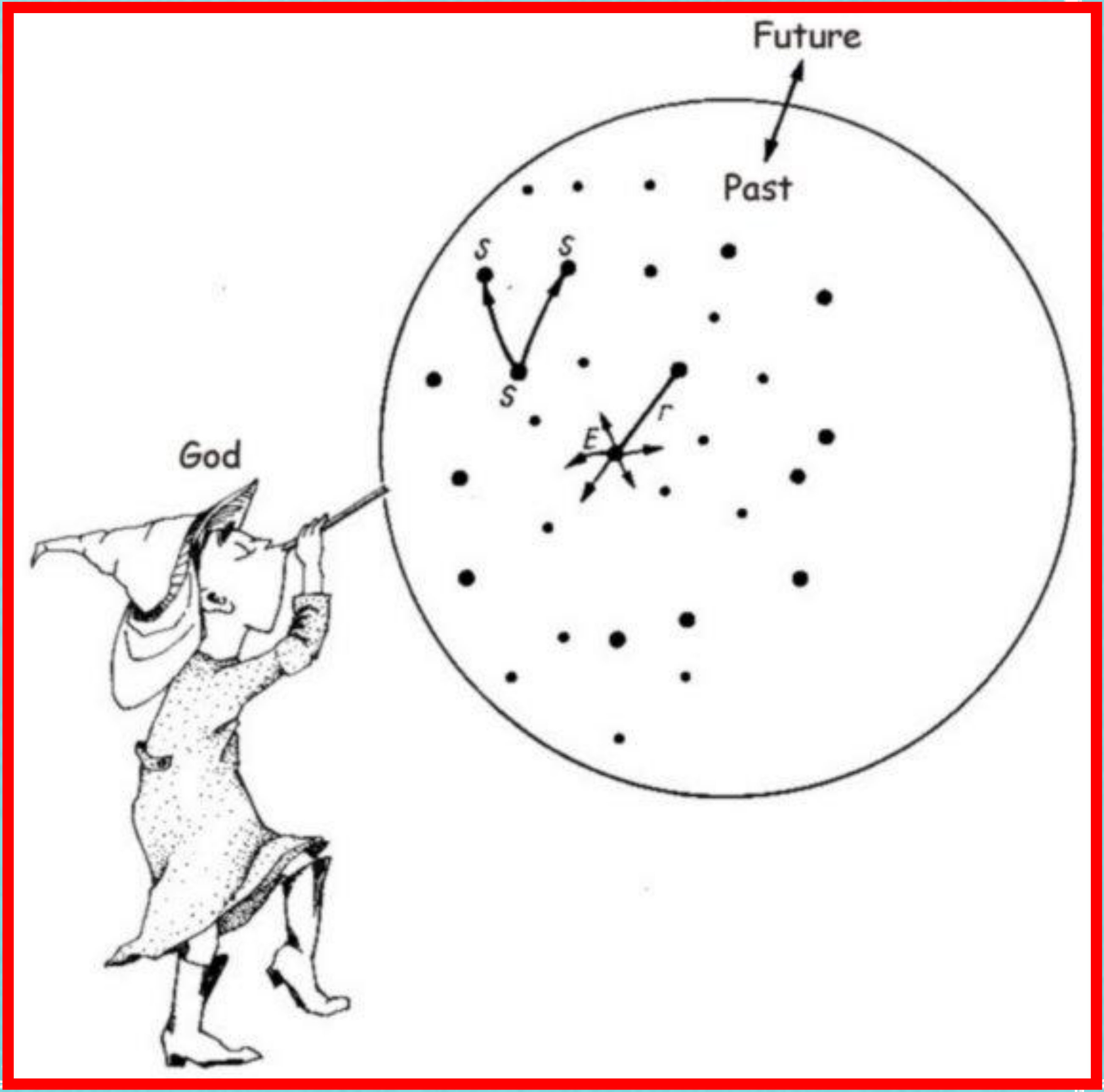


Inflation

- Inflation takes log of problems:
  flatness
  homogeneity
  monopoles

- Unexpected bonus: inhomogeneities

- most likely to distinguish it from contenders



Inflation

- acceleration: existence of states with negative pressure

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

- positive pressure contributes to deceleration
- negative pressure contributes to acceleration

$$\rho + 3p < 0$$

$$w < -1/3$$

Inflation

- if fluid behaves like cosmological constant then

$$w \gtrsim -1$$

- from continuity equation

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\cancel{\rho + p}\right) = 0$$

- gives energy density rho as constant

Inflation

- Constant en. Density gives constant Hubble rate

$$H^2 \sim \frac{\Lambda}{3}$$

- and because $H = \dot{a}/a$

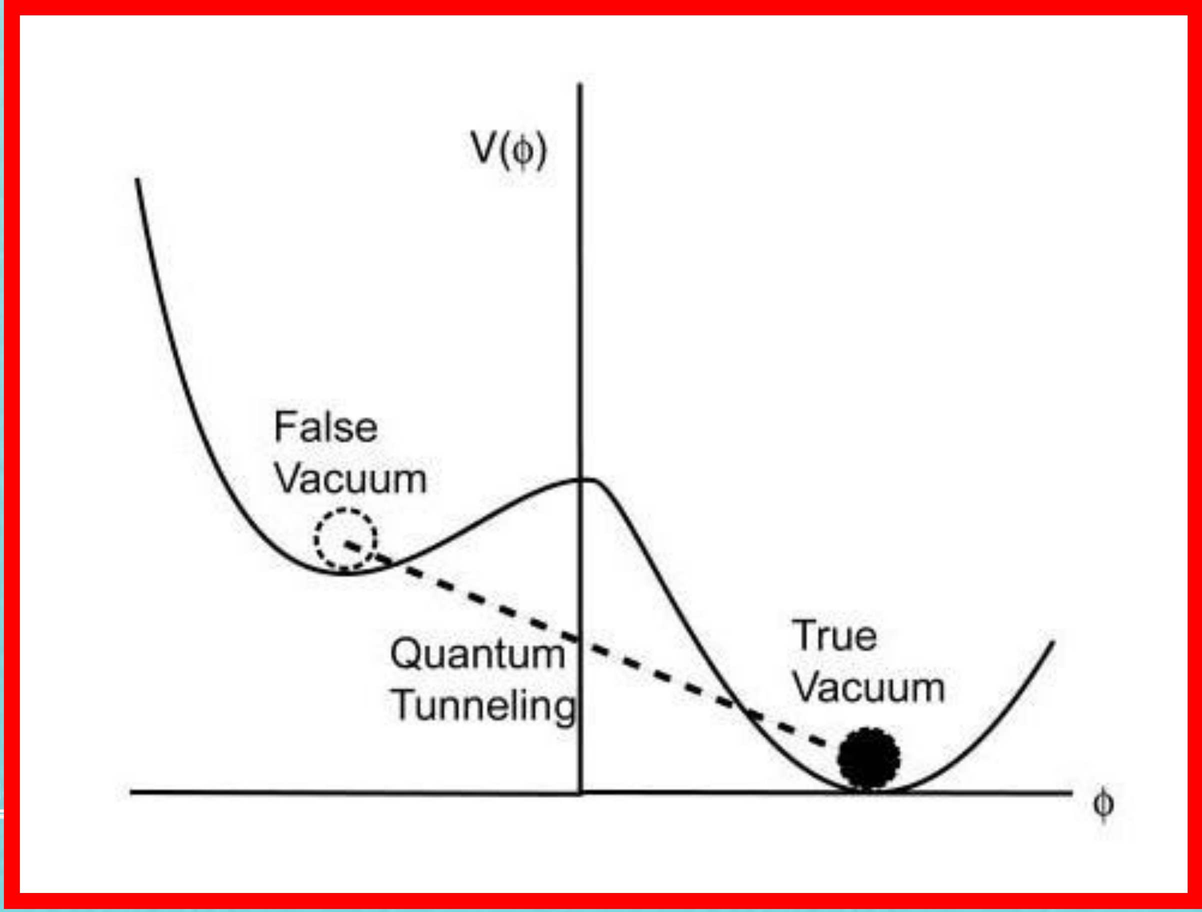
$$\boxed{a(t) \simeq \exp\left(\sqrt{\frac{\Lambda}{3}}t\right)}$$

This is the maths now give us the physics

A. Linde (83) 'Old' inflation:

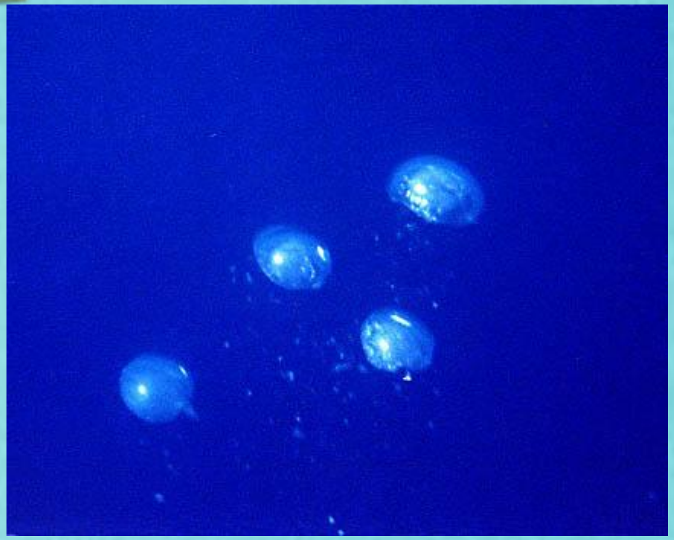
- scalar field sits quietly in a local minimum with non zero energy density

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$
$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

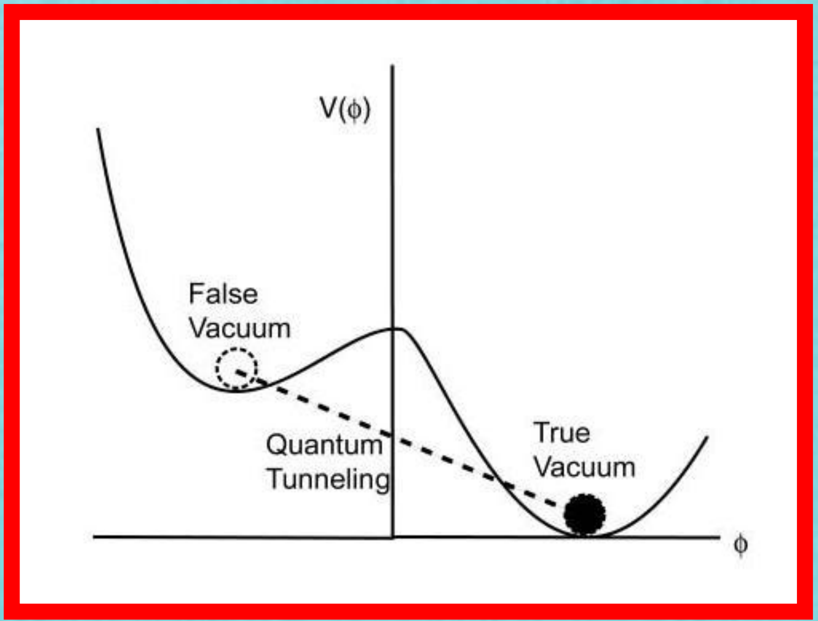


Problems...

- These bubbles aren't gonna meet. Space in between is expanding too fast
  (inflating sea of false vacuum)

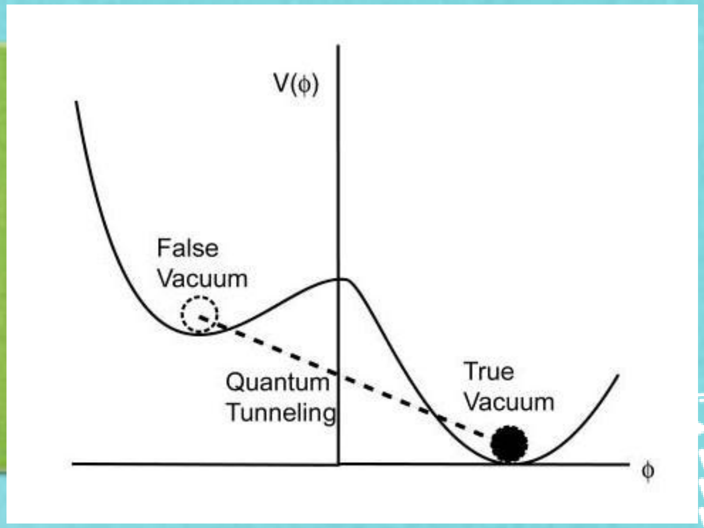


- This acceleration ain't gonna finish
  (we need fluid to be converted to radiation so standard Big Bang can resume)



constant nucleation rate

Problems...



- If you make too many bubbles inflation ends soon. (all bubbles meet) and we dont get enough inflation to solve BB.

- If you make too few bubbles they never meet and you get endless inflation (not good...)

So we need something in between...

Solution - one more d.o.f.
Double Field Inflation

We need nucleation to start slow to allow inflation and then to raise to end inflation.

If we introduce a second field we can make this nucleation rate time dependent.

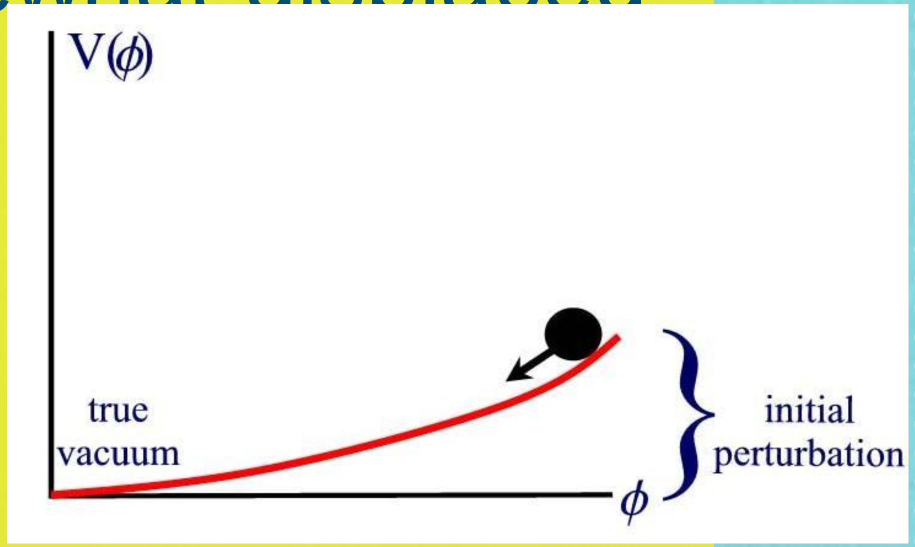
Second field will determine when to begin when to stop

Linde, 90
Adams & Freese, 91

another solution: ‘slow roll’

Linde, 82
Albrecht & Steinhardt, 82

- Field is not in minimum but somewhat displaced and slowly rolling down.



- still get w around -1

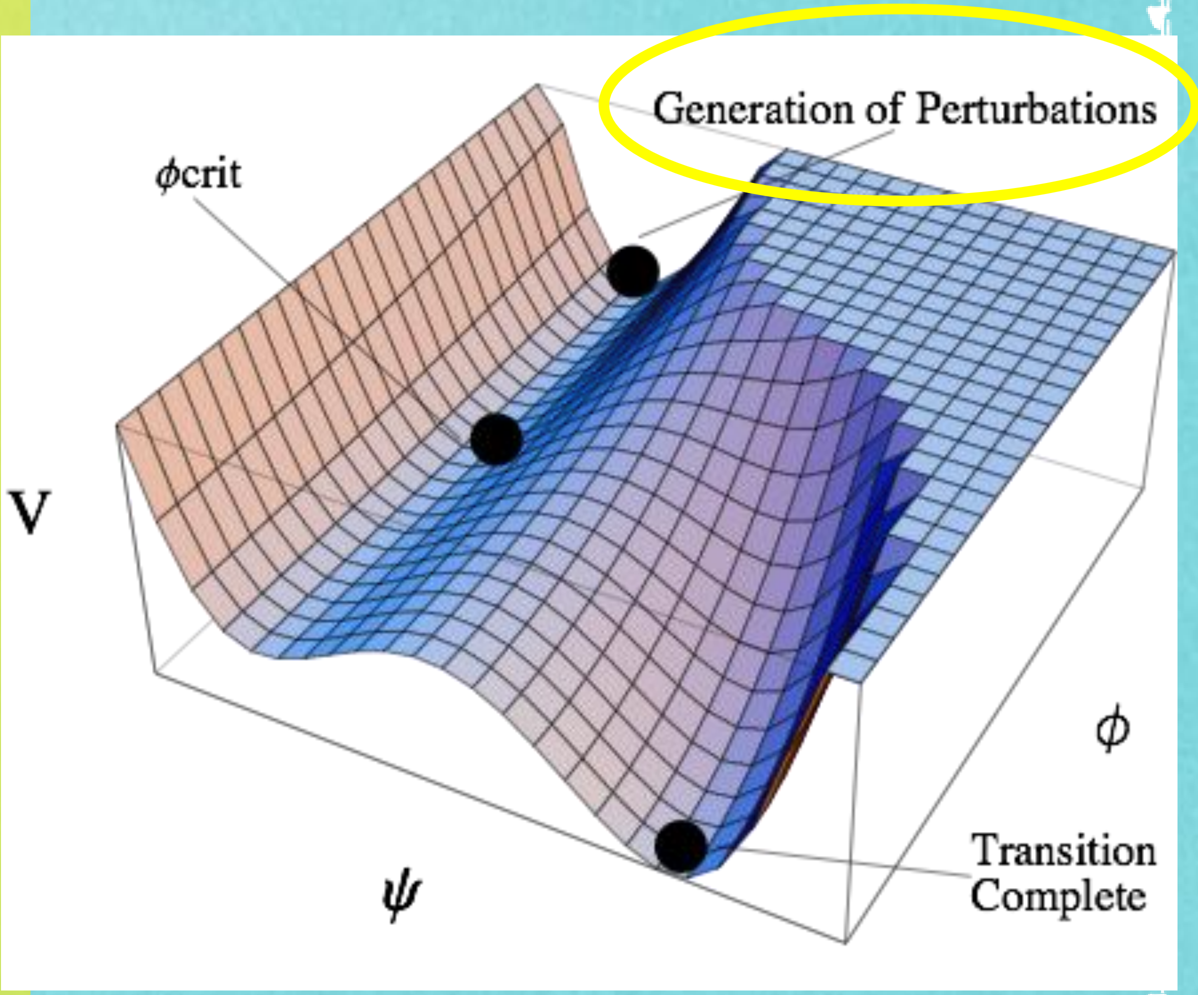
- Make inflation end by speeding up the field, increase slope.

- neglect acceleration and kinetic energy in EoM’s

Double-Field Inflation 1.

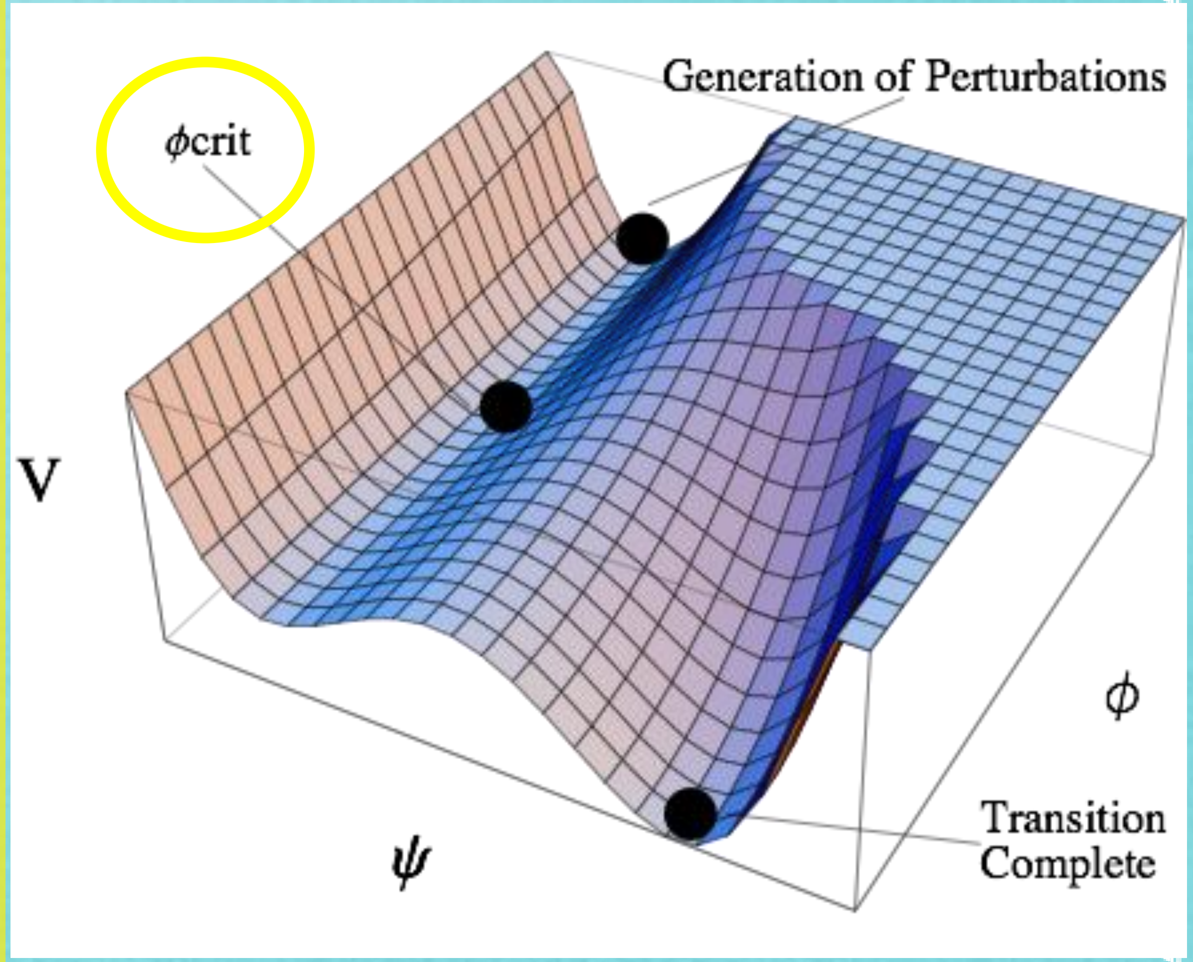
- What do we need?

- generation of perturbations: quiet part of the potential (flat)
- nothing violent is happening (no phase transition)
- almost still field



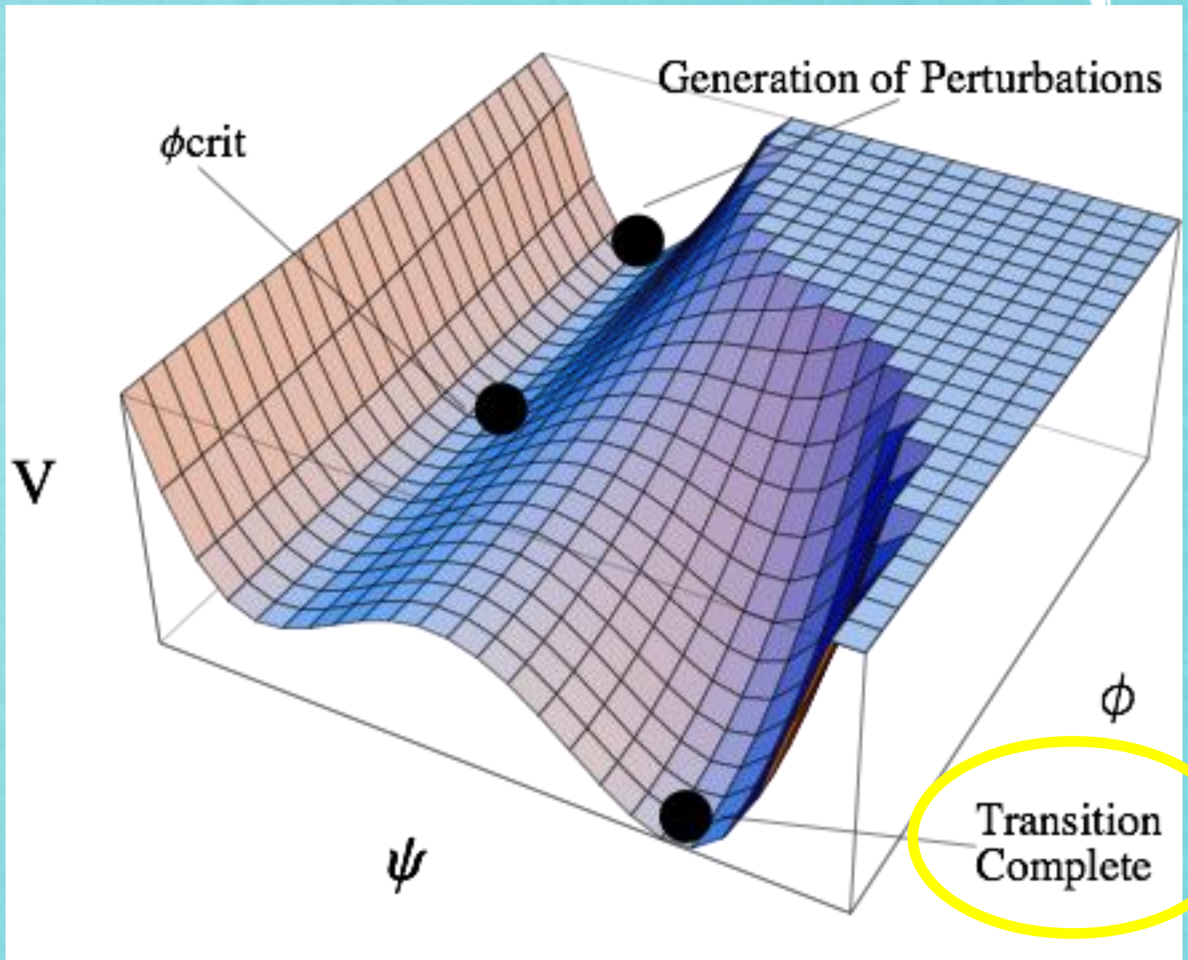
Double-Field Inflation 2.

- What do we need?
- a point where a second minimum starts to develop and eventually becomes more energetically favorable.
- Field starts to quantum tunnel.



Double-Field Inflation 3.

- What do we need?
- bubble nucleation rate to rise large enough to complete the phase transition

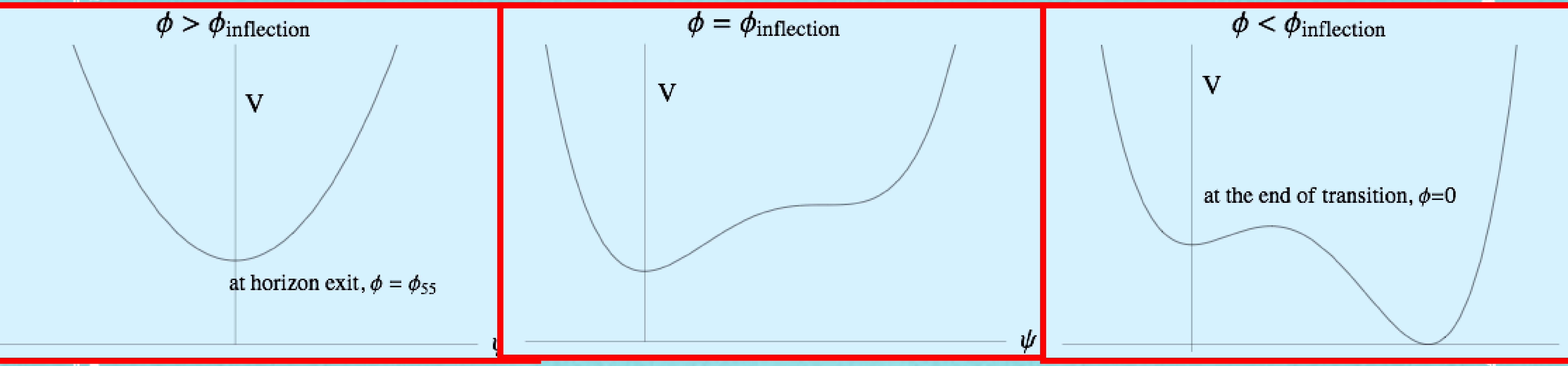


How to get all this?

$$V(\phi,\psi) \;=\; \frac{1}{4}\lambda(M^4+\psi^4)+\frac{1}{2}\alpha M^2\psi^2-\frac{1}{3}\gamma M\psi^3+\frac{1}{2}m^2\phi^2+\frac{1}{2}\lambda\phi^2\psi^2$$

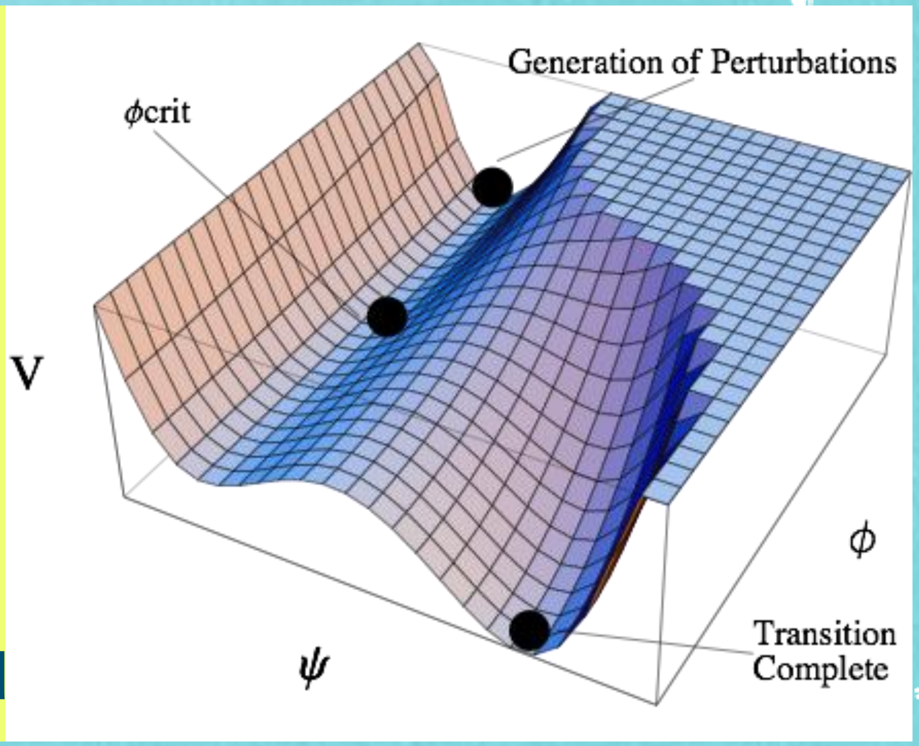
- Cubic term breaks degeneracy and makes one minimum more favorable energetically
- six unknowns... : M, m, λ, λ’, α, γ

3 regions

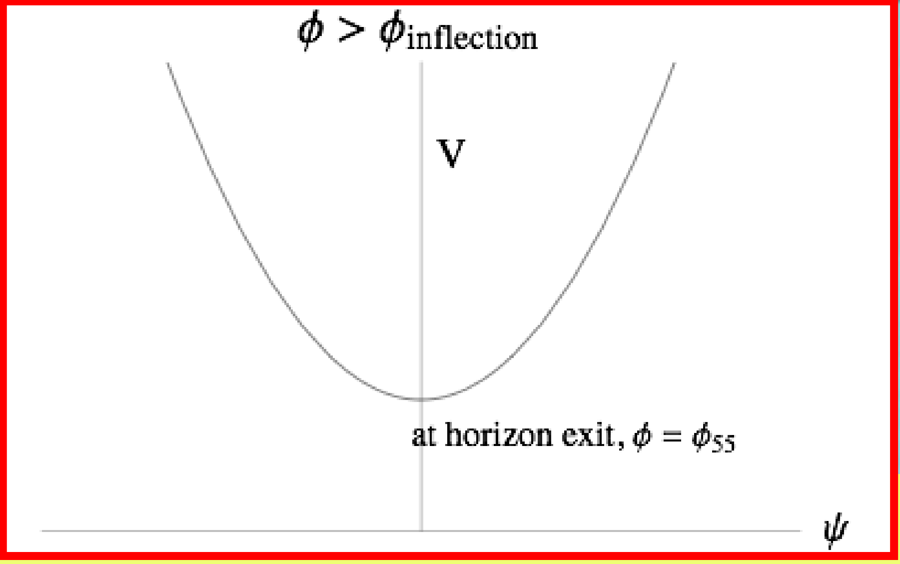


Perpendicular Direction:

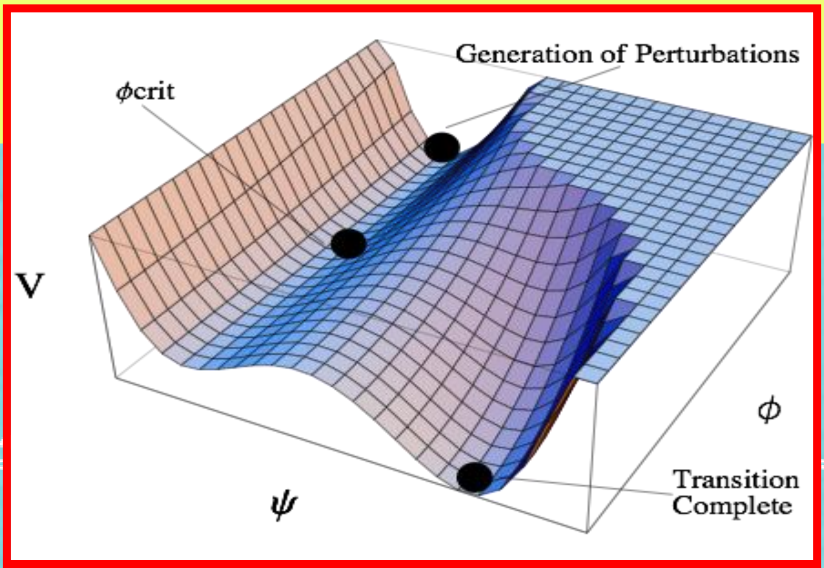
- generation of perturbations
- a second minimum starts to develop
- inflation ends when all space in true vacuu



3 regions:far from minimum



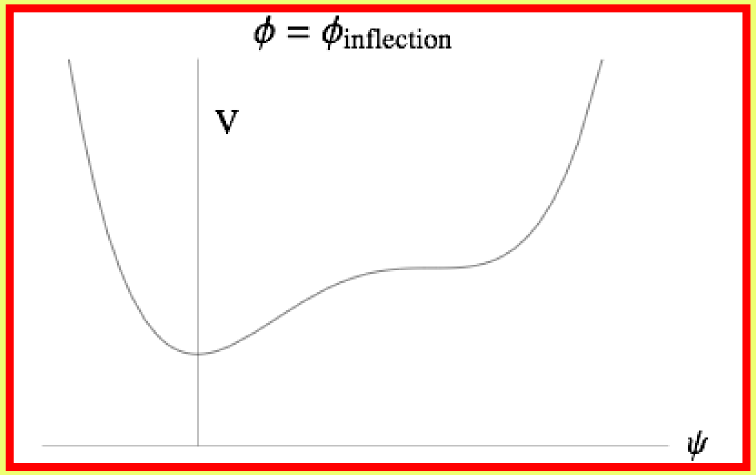
- Φ starts far displaced from minimum and ψ is held in place by coupling to Φ
- dynamics similar to single field slow roll except ψ can provide most of the energy for inflation



3 regions: intermediate

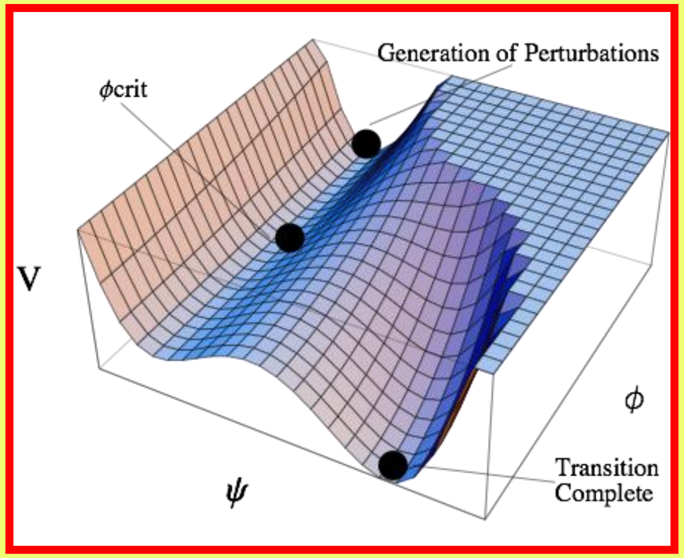
- If parameters adequate a second minimum begins to develop once phi past a certain value. The condition for this to occur is

$$\gamma^2 > 4\alpha\lambda,$$



Field begins to tunnel when the transition becomes energetically favorable.

- Means bubbles of the true vacuum begin to nucleate and expand at speed of light.
- Initially bubble nucleation low. Space outside bubbles accelerating so bubbles never collide.



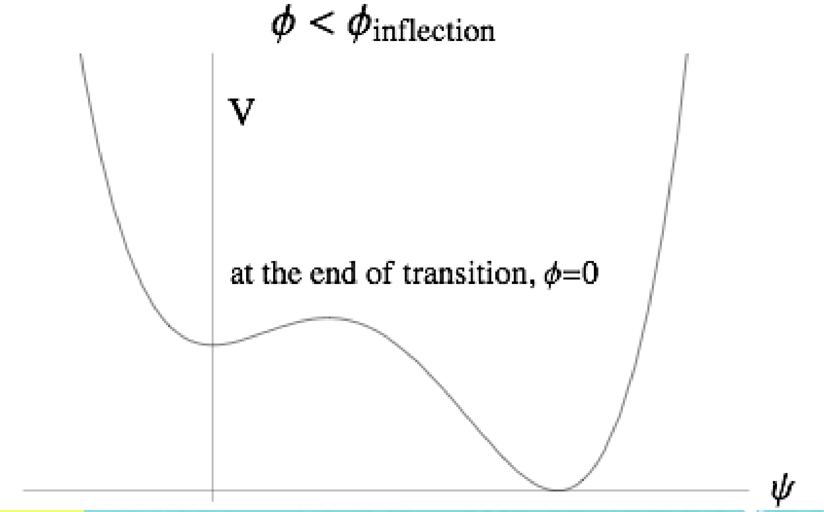
3regions:transition complete

- Phi goes to minimum:

interaction triggers rise in bubbles and all space filled with bubbles of true vacuum

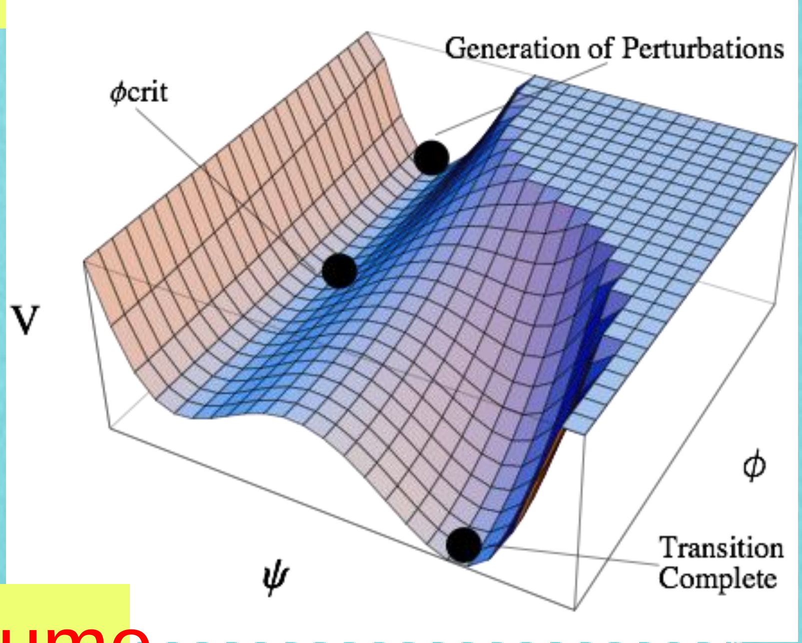
  - collide and thermalize.

- Transition completes. All space in true vacuum



- Nucleation rate is given by

$$p = \frac{\Gamma}{H^4}.$$



Number of bubble per Hubble time per Hubble volume

Bubble nucleation rate

- Nucleation rate is given by $p = \frac{\Gamma}{H^4}$.
- number of bubbles per Hubble time per Hubble volume, i.e. $p = 1$

- limit of zero temperature this is $p = \frac{\lambda M^4}{4H^4} \exp(-S_{\mathrm{E}})$ Callan and Coleman

$$S_{\mathrm{E}} = \frac{4\pi^2}{3\lambda}(2-\delta)^{-3}(\alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3)$$

Euclidean 4 - action
(Adams ’93)

lots of bubbles...

$$p = \frac{\lambda M^4}{4H^4} \exp(-S_{\mathrm{E}})$$

$p = 1$ when inflation ends

$$S_{\mathrm{E}} = \frac{4\pi^2}{3\lambda}(2-\delta)^{-3}(\alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3)$$

Euclidean 4 - action
(Adams '93)

$$\delta = \frac{9\lambda\alpha}{\gamma^2} + \frac{9\lambda\lambda'\phi^2}{\gamma^2 M^2}$$

keep an eye for this one

will be important for finding which models are good

but... do you always get bubbles?

- If potential too steep, inflation ends before transition completes.
- Means we don't care about what how phase transition proceeds, this case looks like single-field slow-roll

- What determines process to end inflation is which value occurs first

$$\phi_{\rm end} = \max(\phi_\epsilon, \phi_{\rm crit})$$

How to get all this?

$$V(\phi,\psi) \;=\; \frac{1}{4}\lambda(M^4+\psi^4)+\frac{1}{2}\alpha M^2\psi^2-\frac{1}{3}\gamma M\psi^3+\frac{1}{2}m^2\phi^2+\frac{1}{2}\lambda\phi^2\psi^2$$

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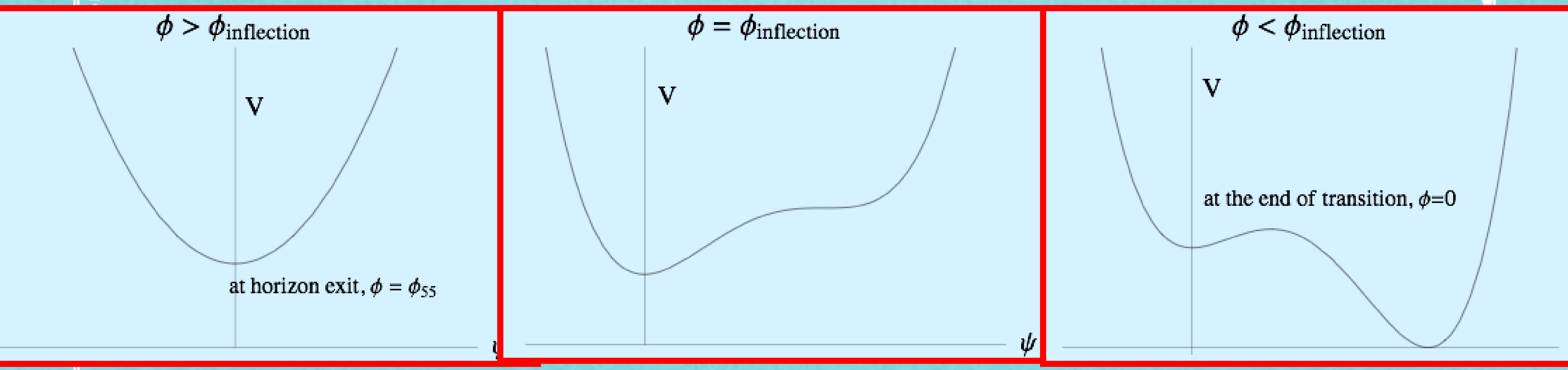


constraining the model - 1.

- six unknowns... : M, m, λ, λ', α, γ

$$V(\phi,\psi) \;=\; \frac{1}{4}\lambda(M^4+\psi^4)+\frac{1}{2}\alpha M^2\psi^2-\frac{1}{3}\gamma M\psi^3+\frac{1}{2}m^2\phi^2+\frac{1}{2}\lambda\phi^2\psi^2$$

we don't want residual energy at the end

… (not looking for a cosmological constant this time) …

$$V(\phi=0,\psi=\psi_{min}) \;=\; 0$$

gives us one of the couplings in terms of the others

$$\gamma=\sqrt{\frac{-\alpha^2+9\alpha\lambda^2+\sqrt{(\alpha^2+3\lambda^2)^3}}{3\lambda}}$$

constraining the model - 2.

- six unknowns... : M, m, λ, λ', α, γ

use WMAP amplitude normalization to relate masses

$$M \sim m^{2/5}$$

and now fix λ = λ' = 1

So we're left with M and α

Probe this parameter space to see which values are allowed by observations

constraining the model - 3.

- 1.Choose M and α
- 2. Find out if these give you bubbles or “single field inflation” by determining how inflation ends.
- 3. Use efolds equation to evolve back to the epoch when perturbations were generated

$$N(\phi_1,\phi_2) \equiv \ln\frac{a_2}{a_1} \sim -\frac{8\pi}{m_{\rm Pl}^2}\int_{\phi_1}^{\phi_2}\frac{V'}{V}\,d\phi\,.$$

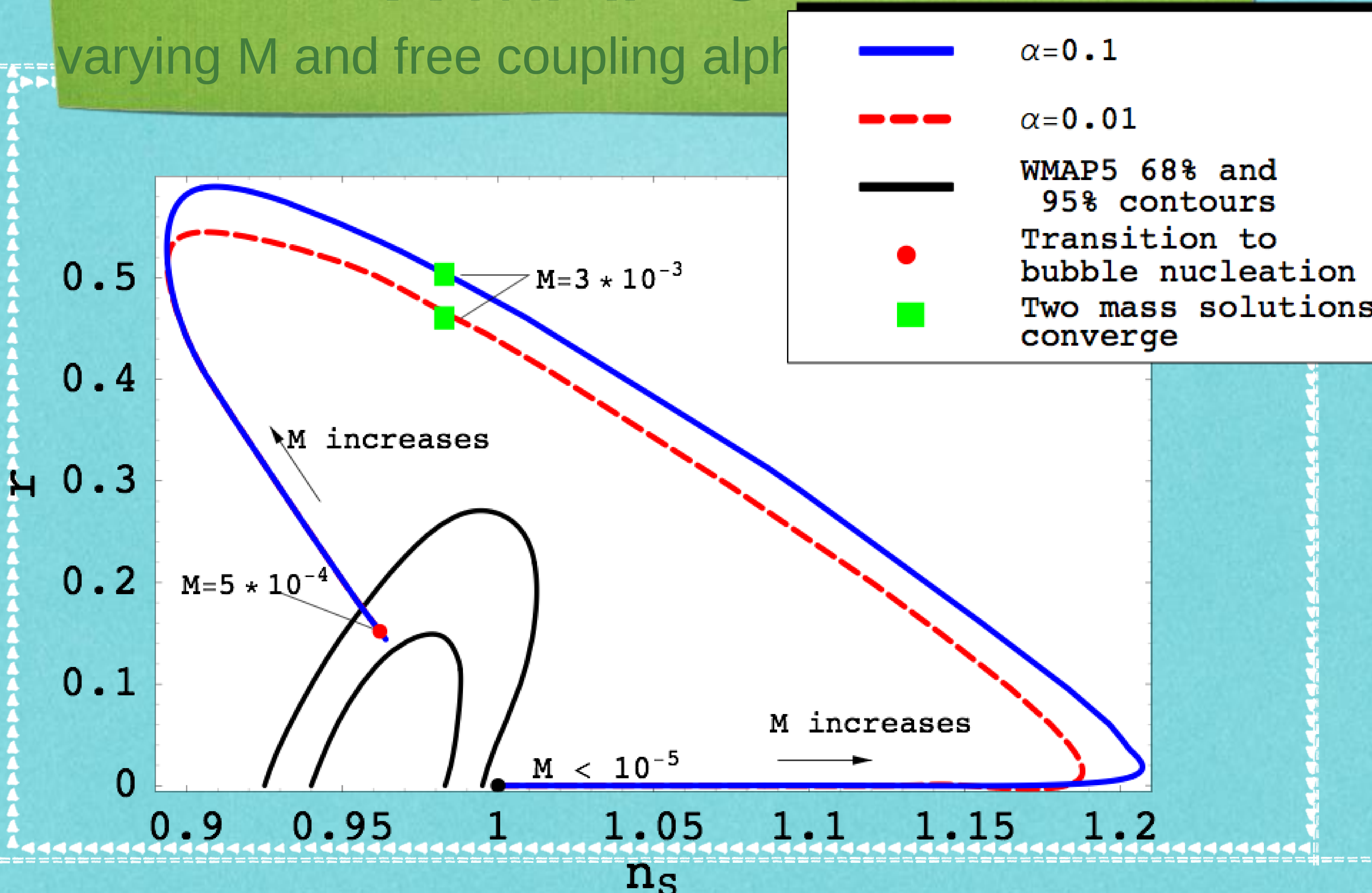
- 4. Compute the scalar and tensor tilt at that time by the usual methods

$$\begin{aligned} n_{\rm S}-1 &= -6\epsilon+2\eta\,; \\ r &= 16\epsilon\,, \end{aligned}$$

- 5. Find your location in the nS -r plane.

WMAP 5

varying M and free coupling alph

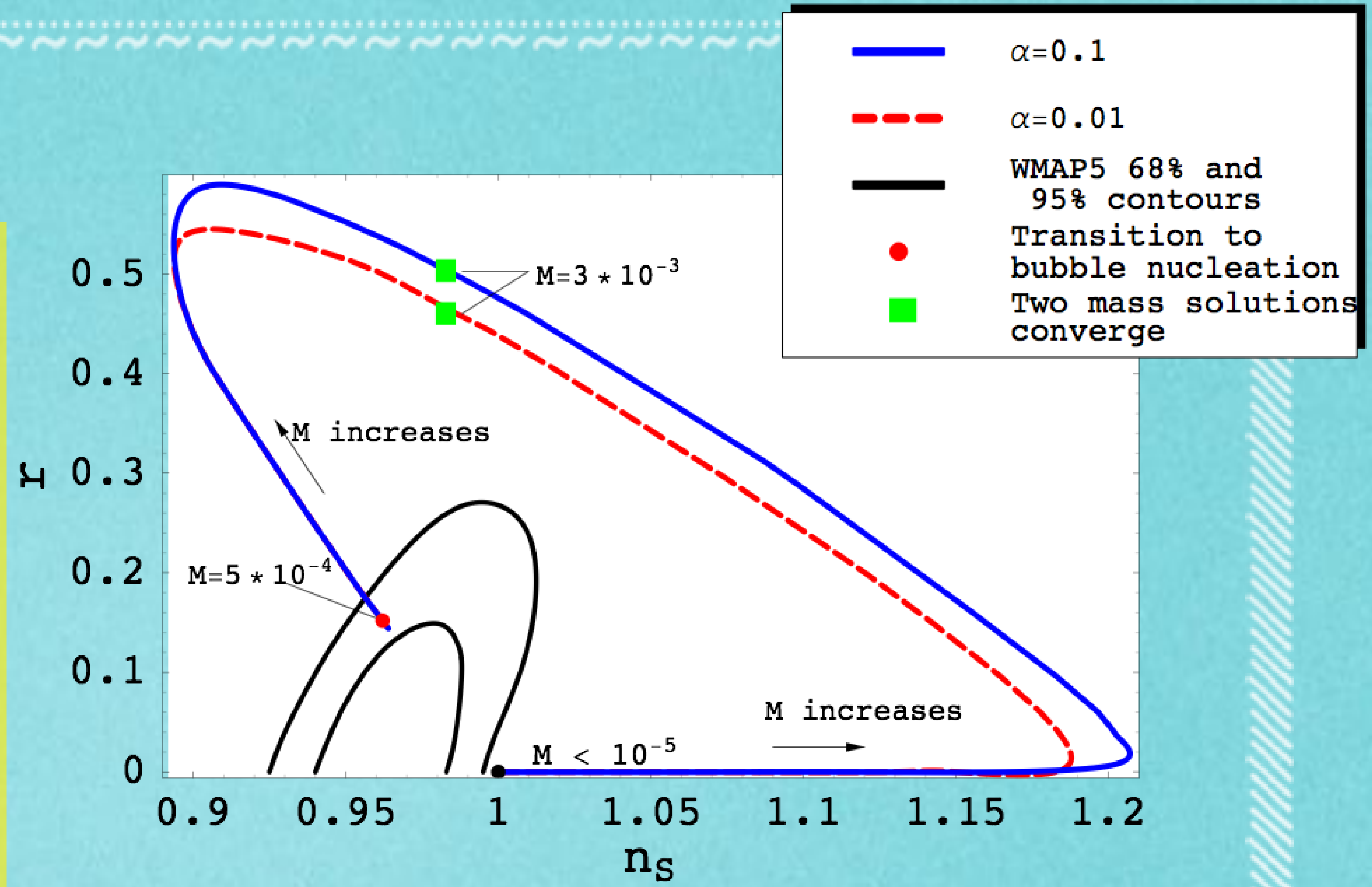


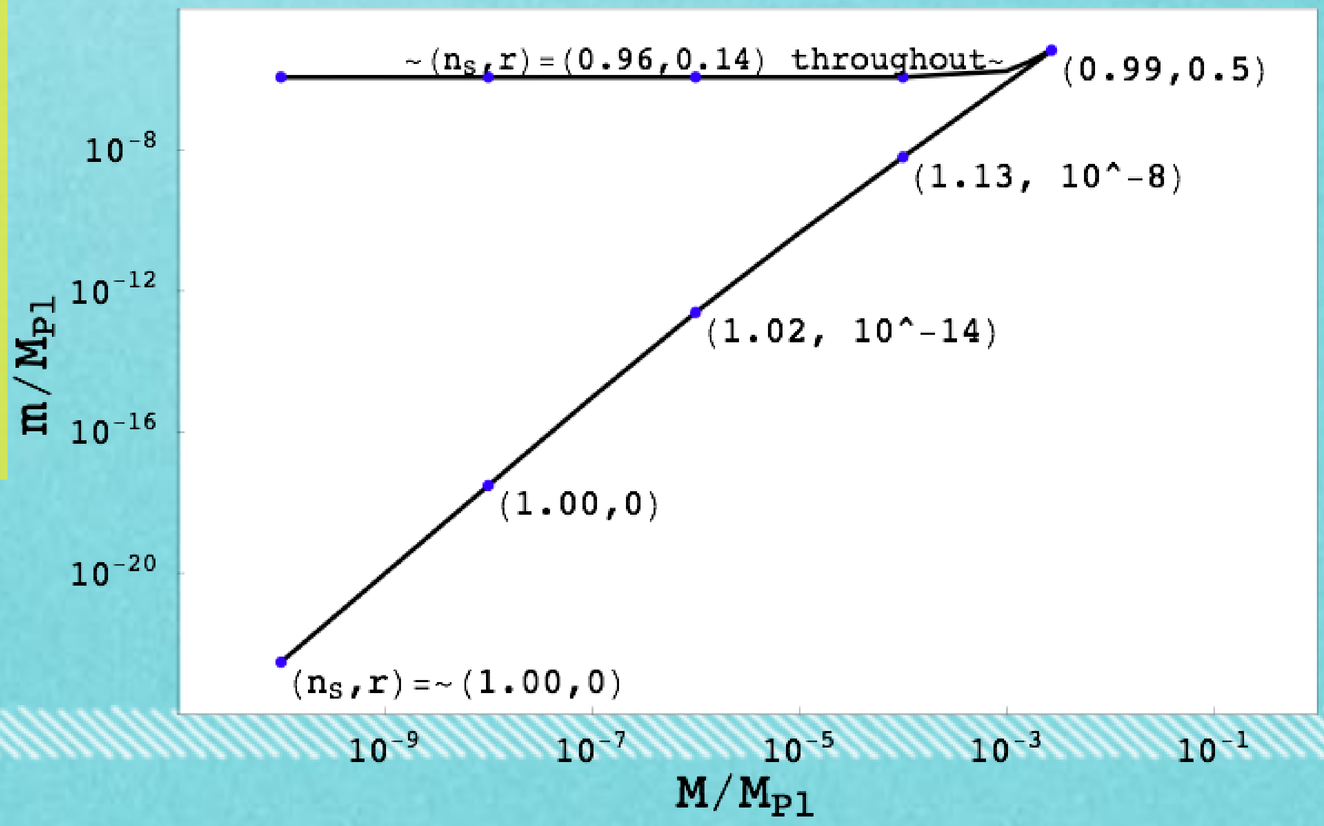
CMB amplitude: two solutions
false vacuum domination
inflaton domination

Want intermediate regime as well:

$$\lambda M^4 \sim m^2\phi^2$$

- Keep full expressions throughout.
- Allows to probe full regime. and draw continuous line in
- n-r plane



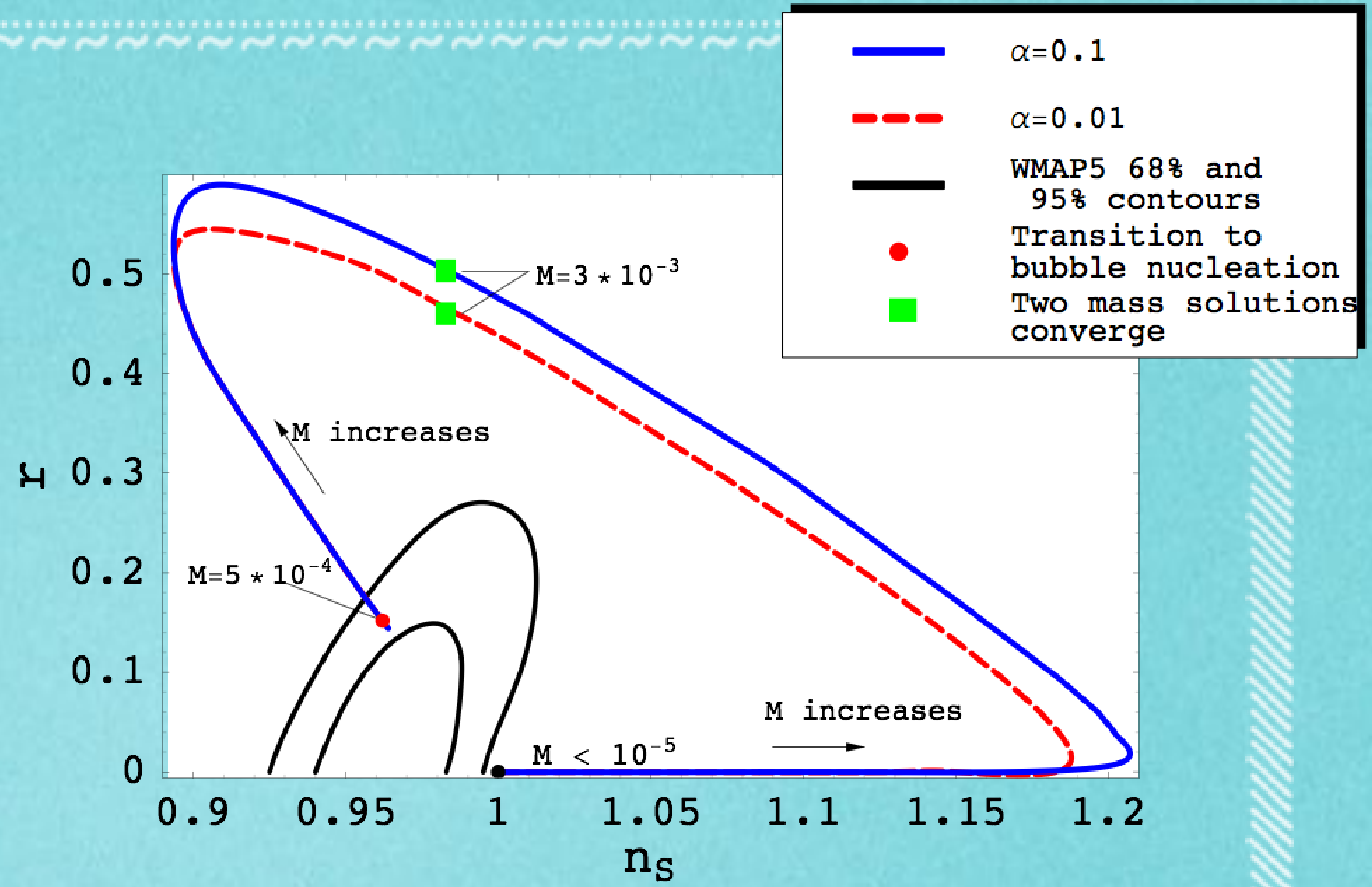


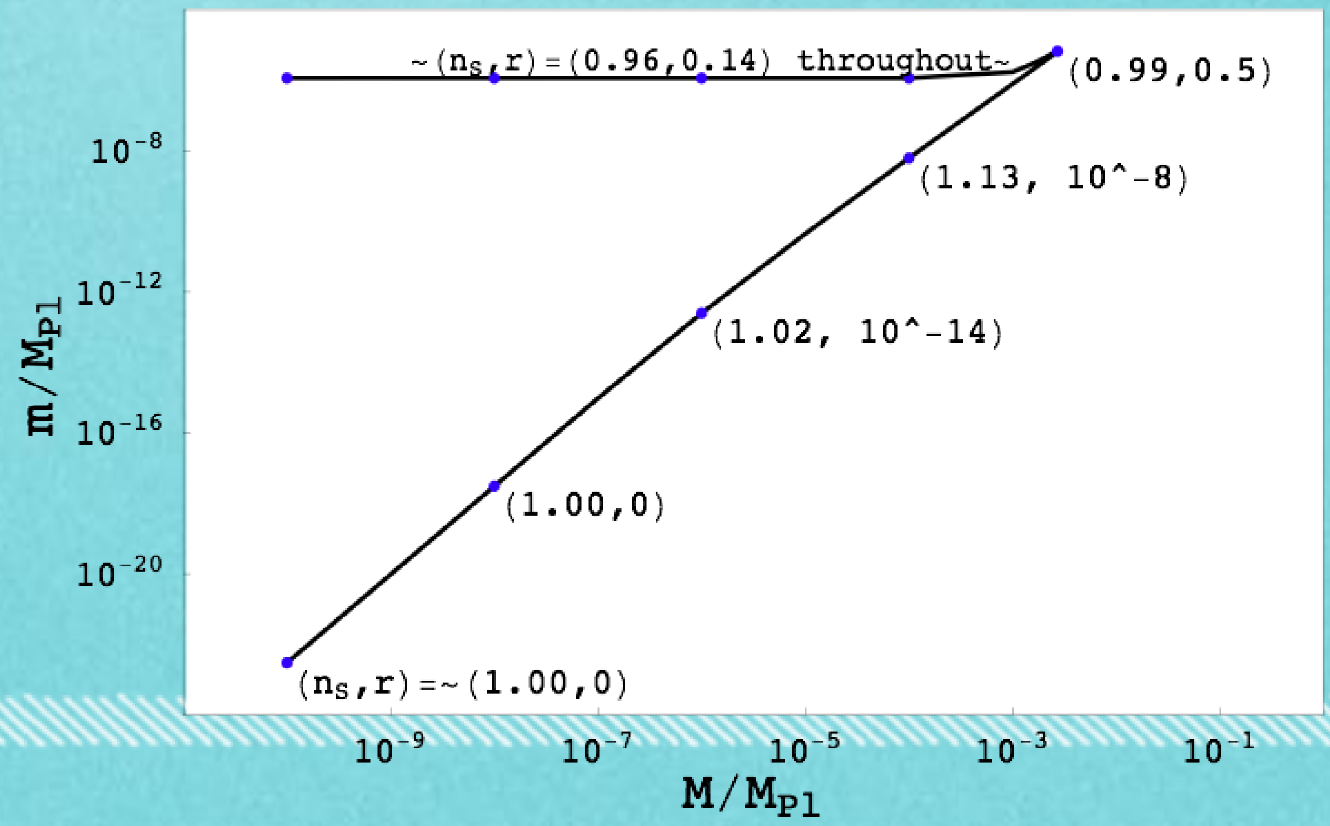
3 Mass Regimes

1. Lower branch.

- Start off in the large M regime (mass of inflaton very small), blue tilted spectrum.

- False vacuum domination

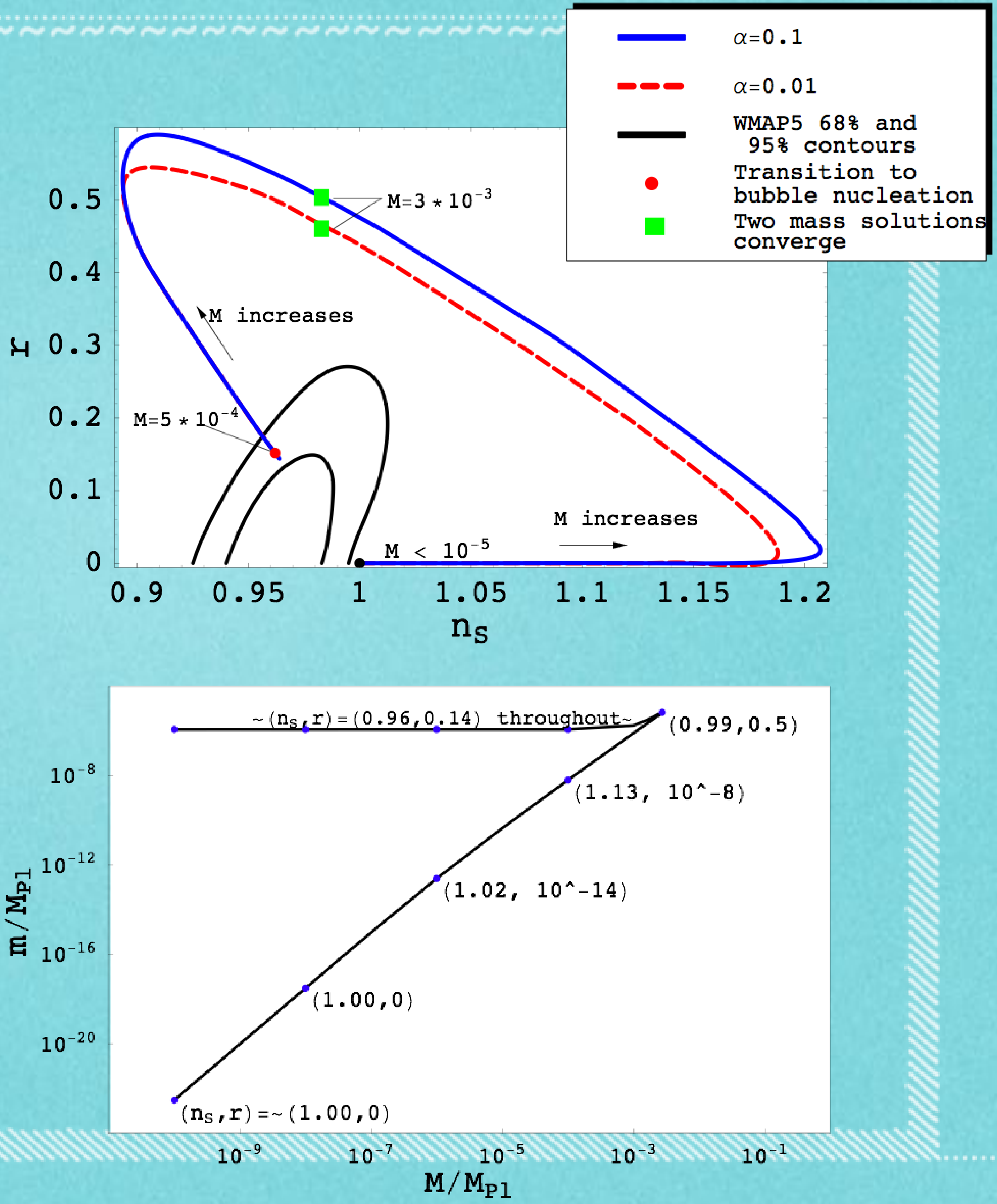




2. As M increases, m increases as well (remembe $M \sim m^{2/5}$

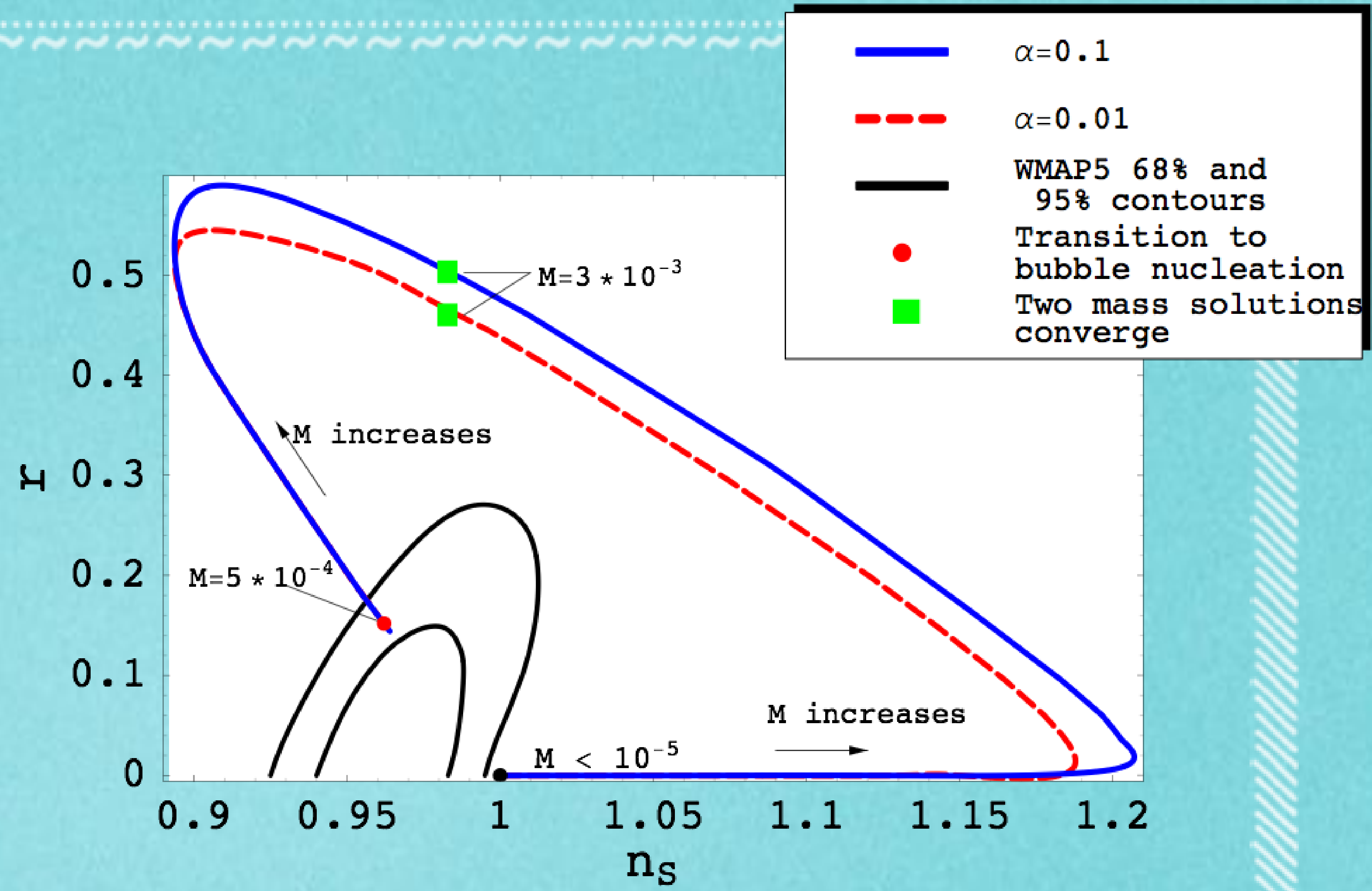
nS deviates from unity until the approximation breaks down and the two masses become comparable.

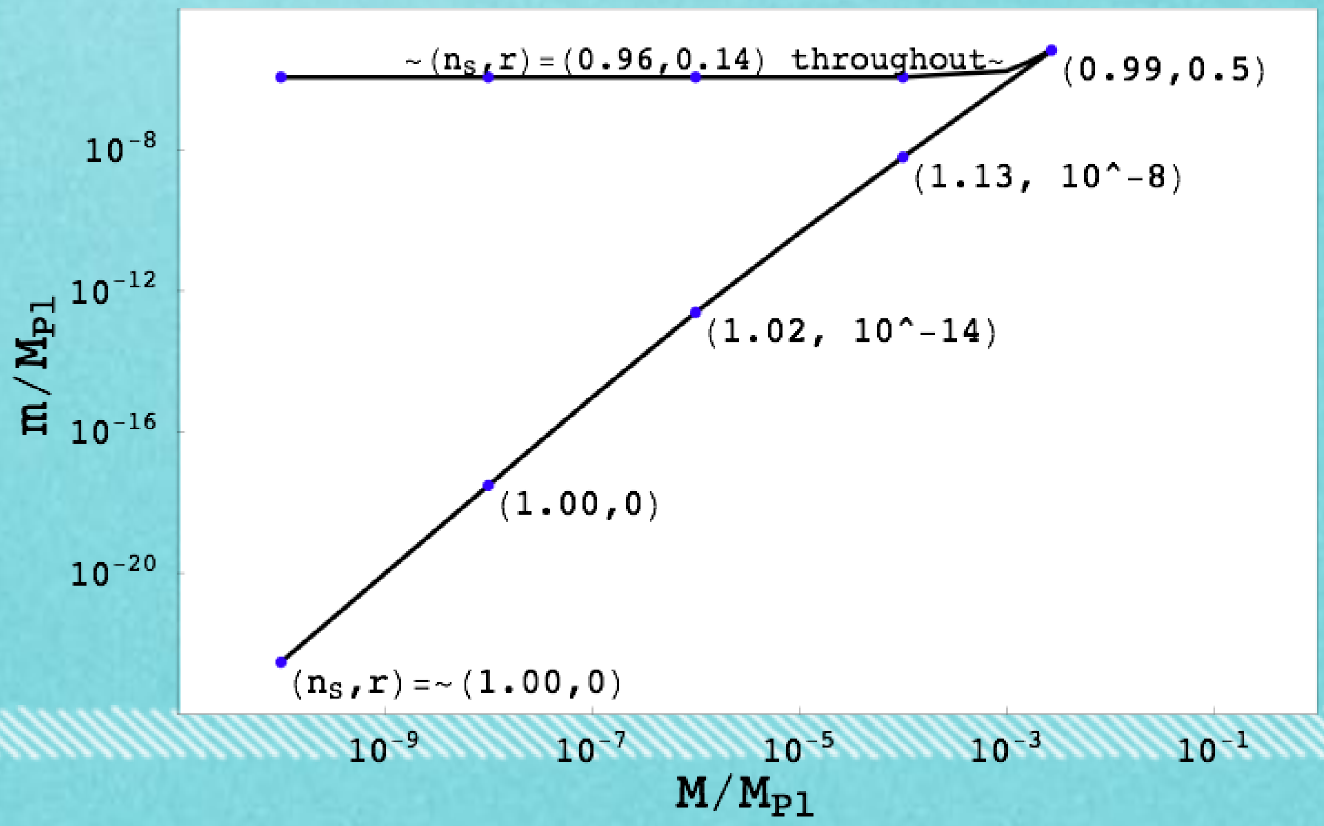
The intermediate regime



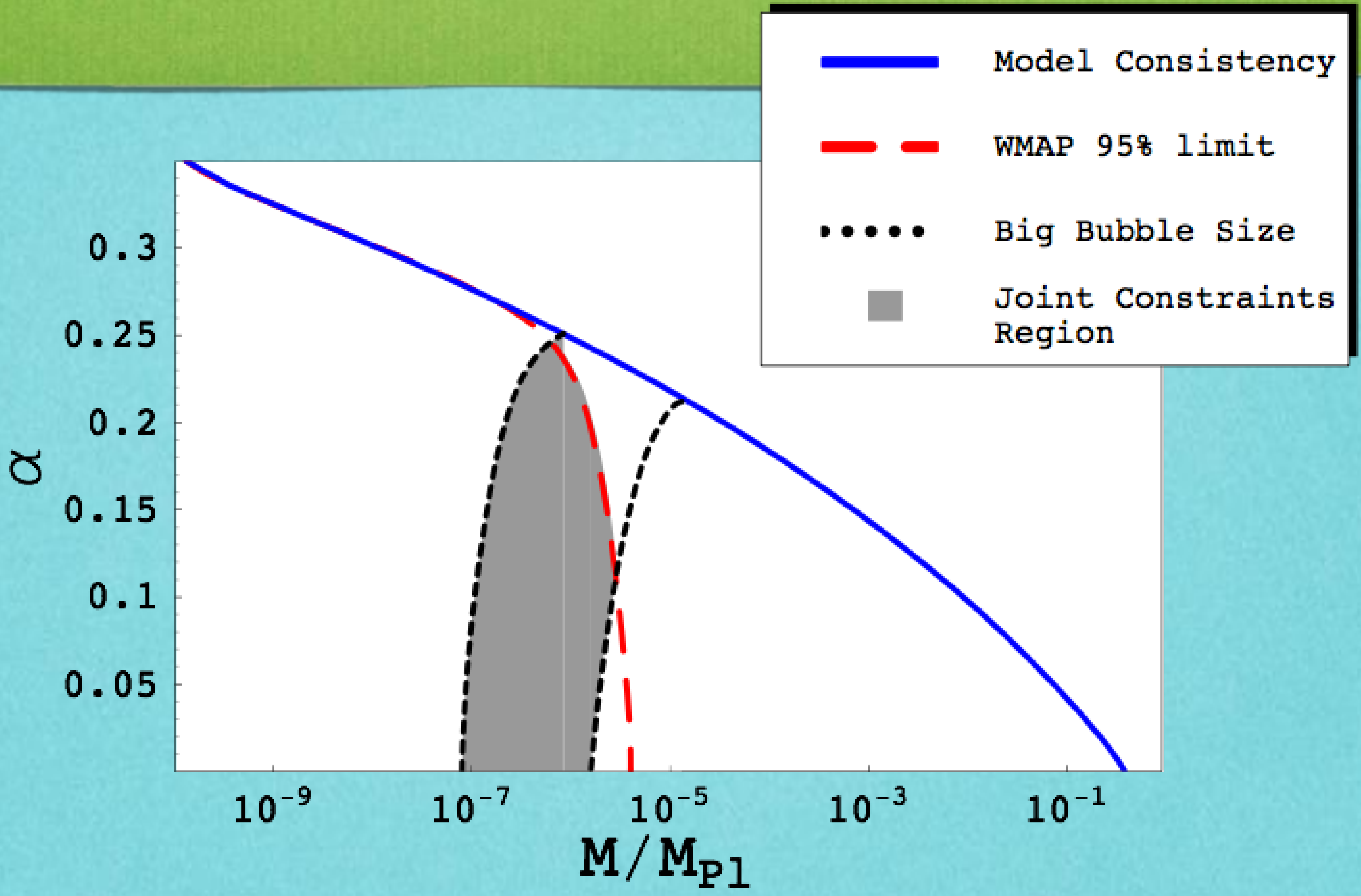
3. Inflaton domination
Upper branch
Start off in inflaton domination.
nS-r independent of M stays constant throughout this branch until two solutions converge at

$$M \sim 10^{-3} M_{\rm Pl}$$



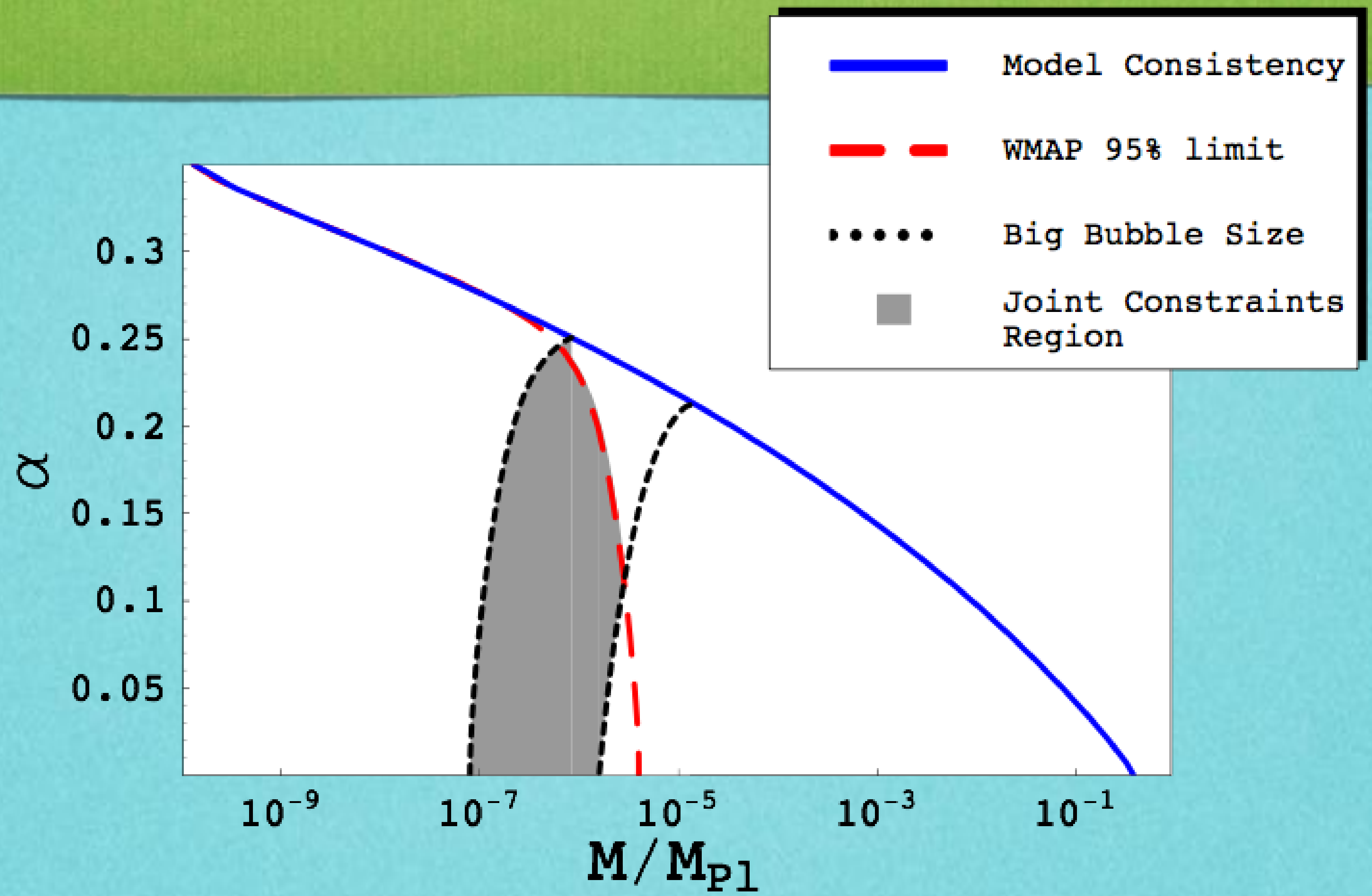


More Constraints



- size of bubbles at horizon exit
- model consistent line
- wmap line

More Constraints



- bubbles at CMB not larger than 20 h^{-1} Mpc
- filling fraction at horizon exit smaller than 10^{-5}
- means percolation rate smaller than 10^{-5}
- from this small value must increase to reach unity at the end of inflation
- expect this contrasts with scale invariance from observations

Conclusions

•Despite recent measurements of nS < 1:

• viable double field inflation models with the nucleation of bubbles and match all observations.

•Tension between nS ~ 1 and voids in the CMB

•topological defects possibility

•relatively easier to realize within particle physics

•graceful exit

Stay tuned!

PLANCK AND **HERSCHEL** LAUNCH SUCCESSFULLY ON MAY 14TH FROM FRENCH GUIANA

"We could probably power a small town for a week with all the excitement in the cosmology community today."