Recent Progress on Cyclic Universe Models

w/ Neil Turok
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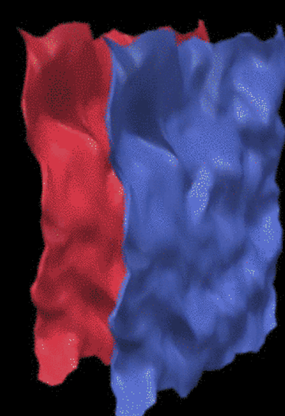
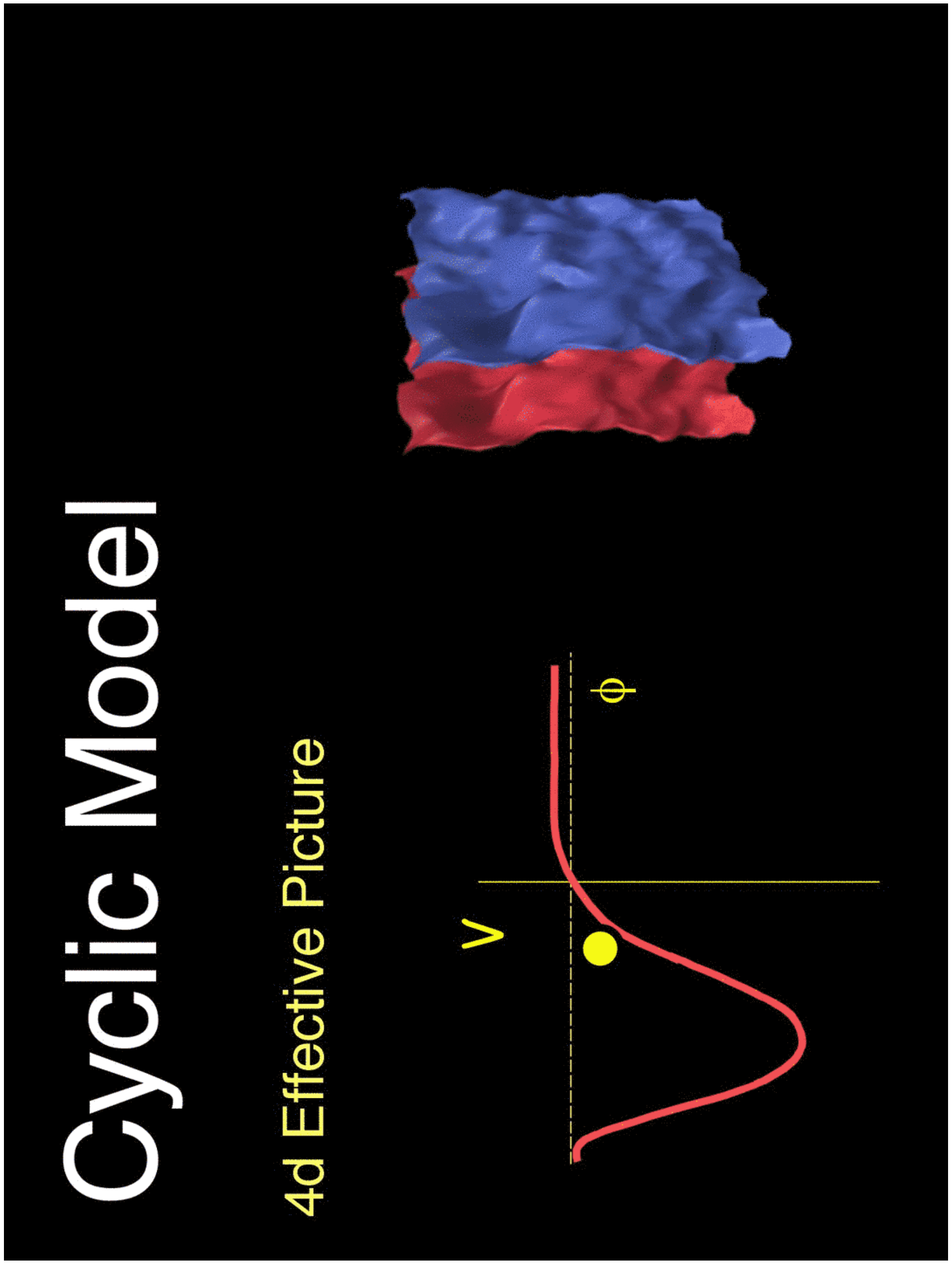
Cyclic Model

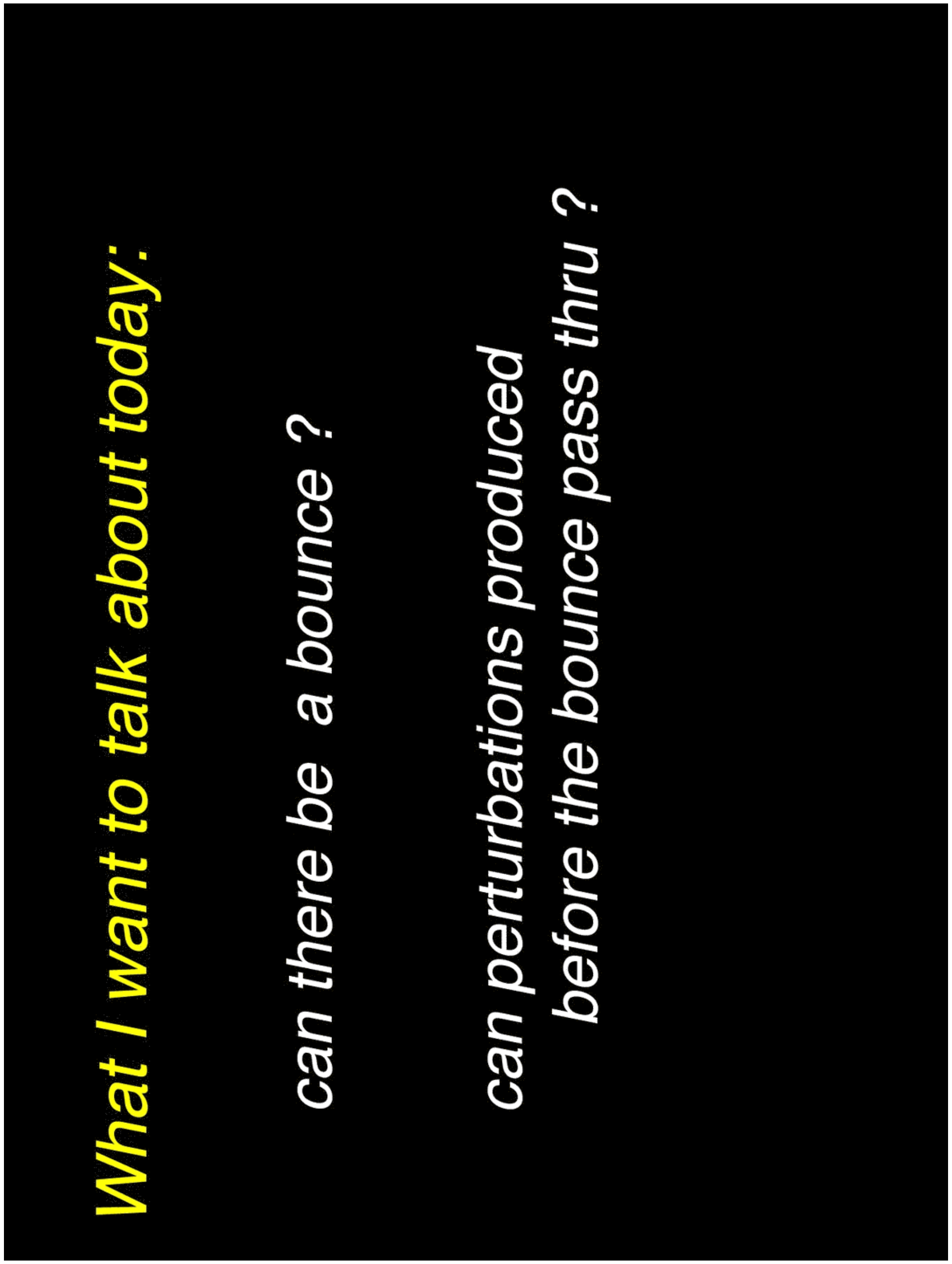
5d Brane Picture

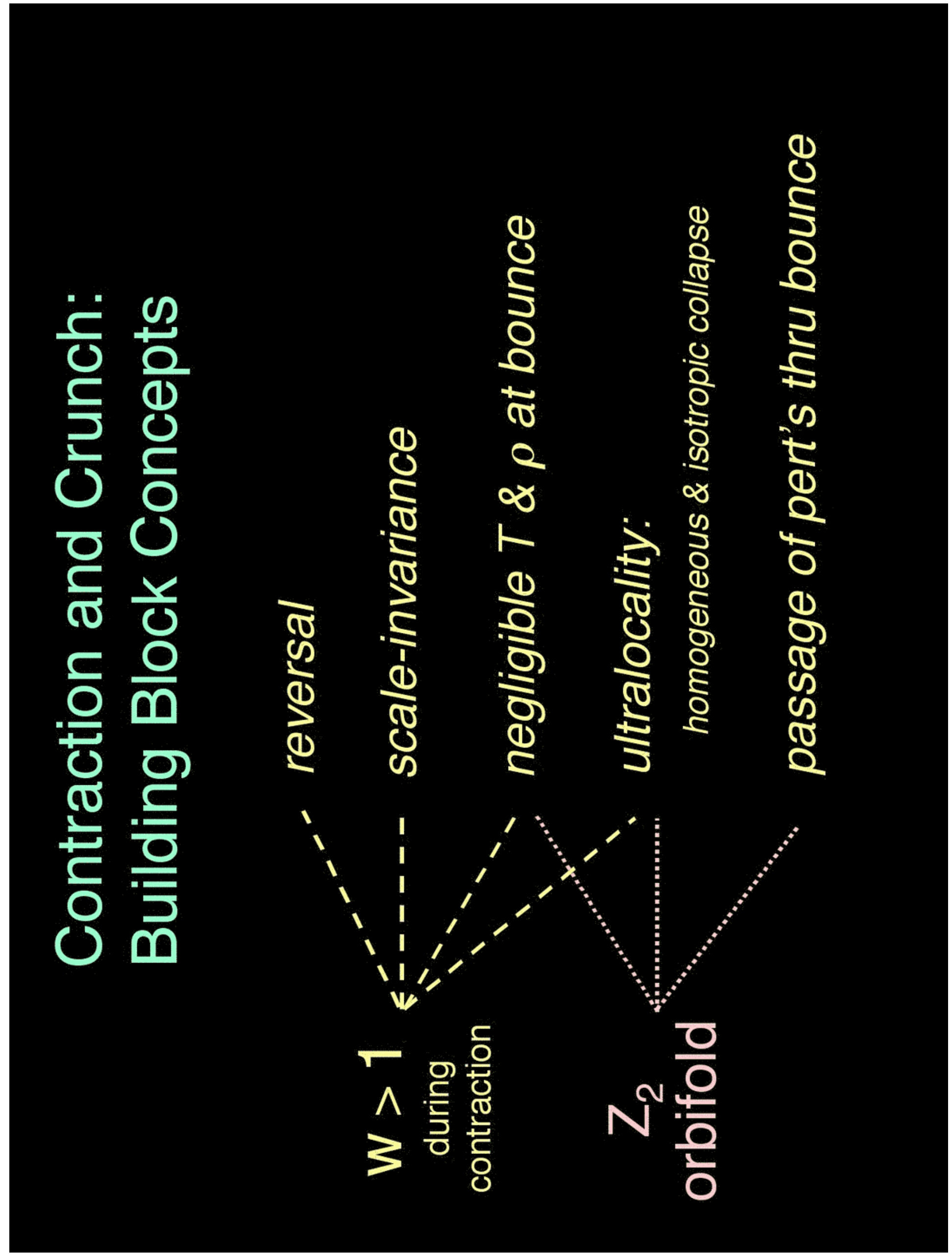
- "bang"
- radiation
- matter
- dark energy
- "contraction"
- "crunch"

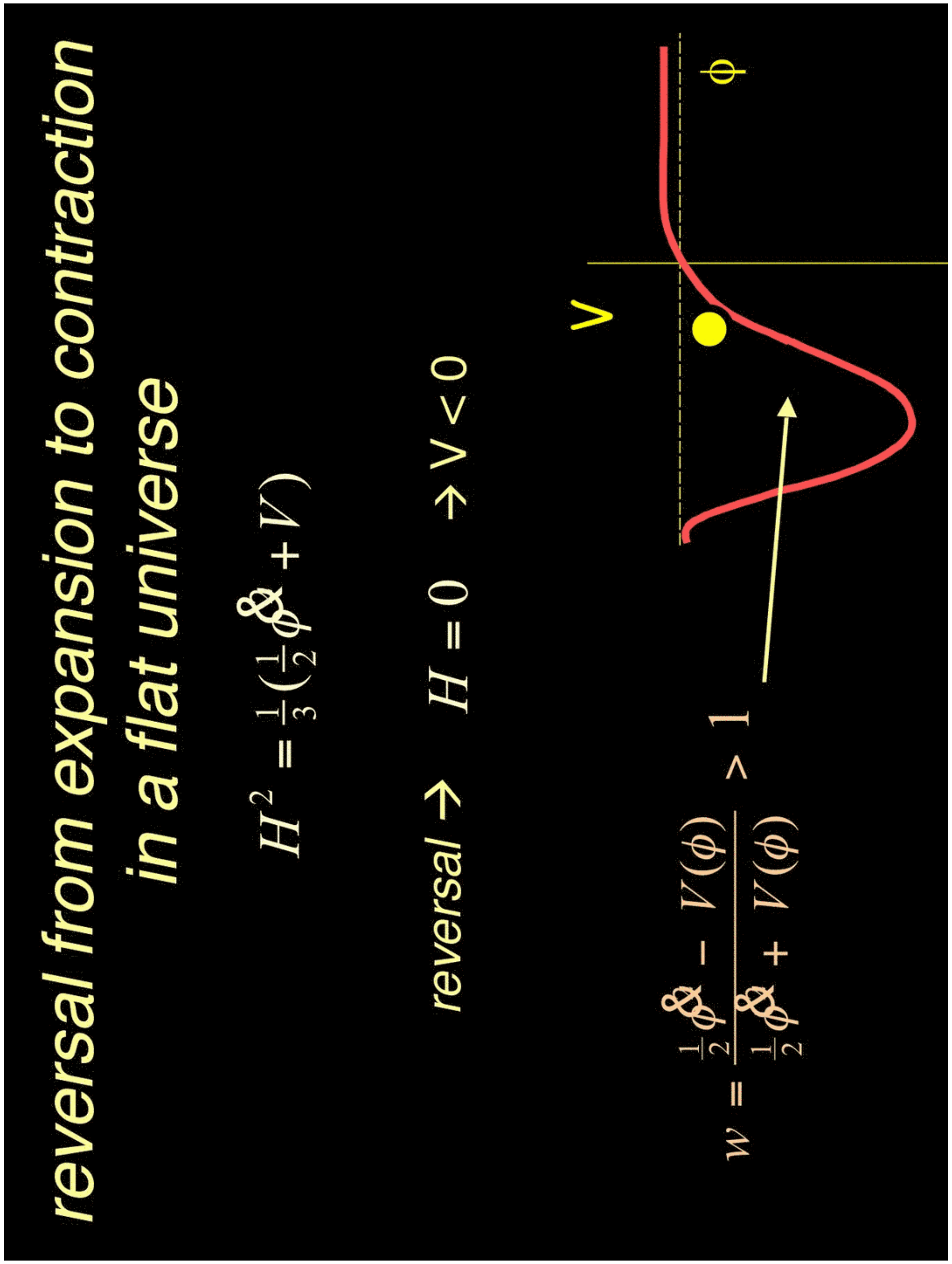


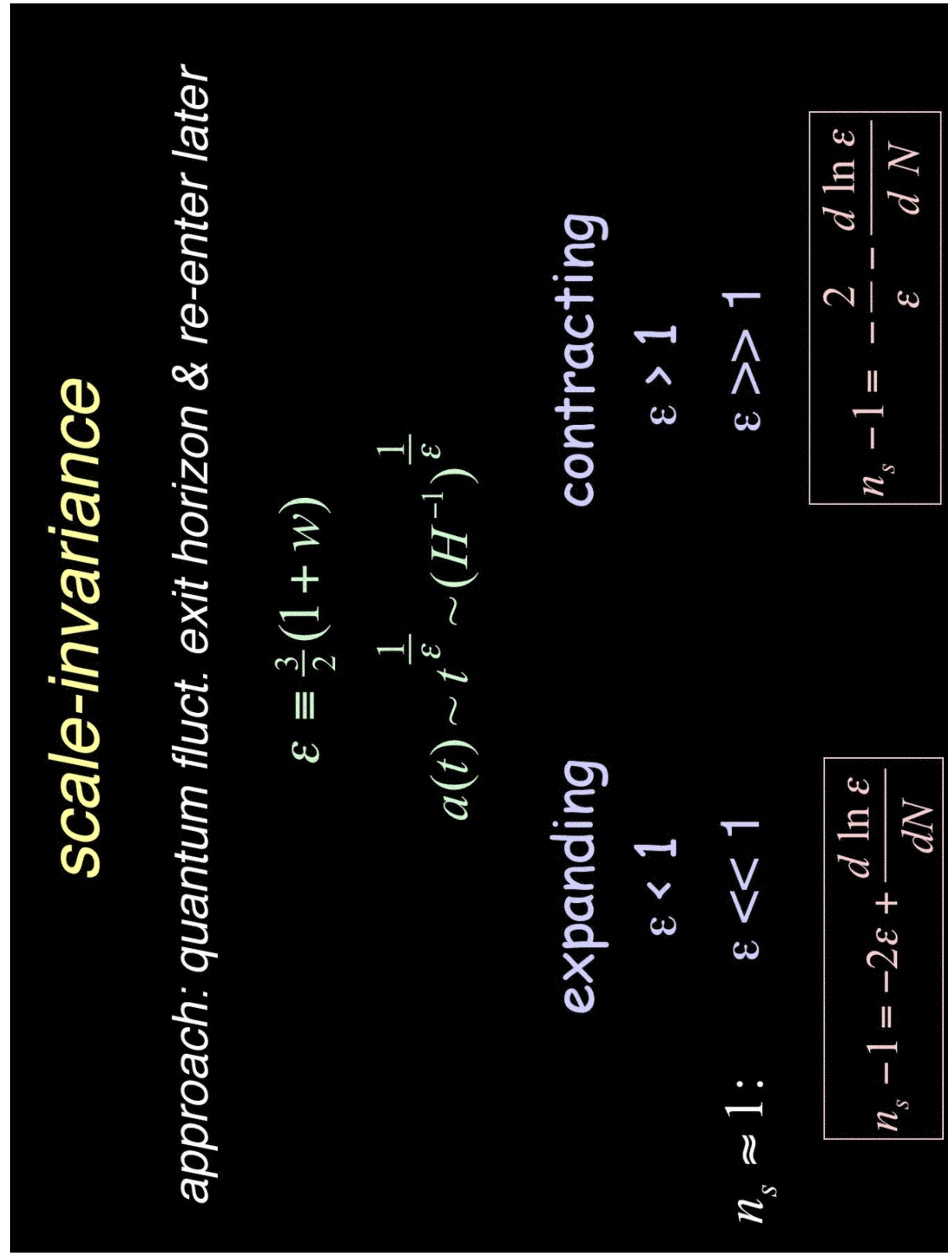

Cyclic Model
4d Effective Picture
V
φ

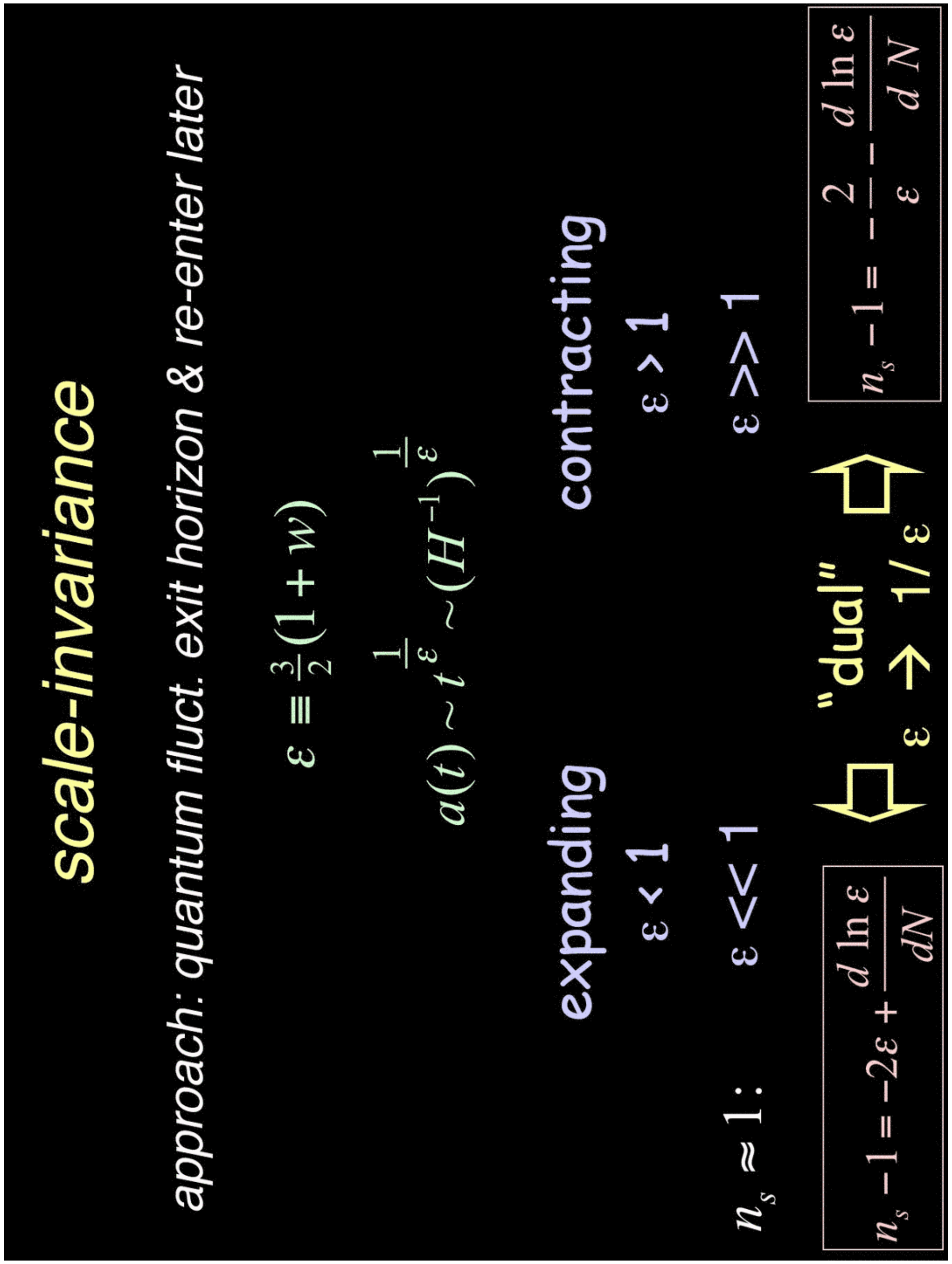

Many interesting issues
is cycling better/worse than inflation?
finite or infinite number of cycles ?
eternal ?
holographic bounds ?
distinctive predictions ?


What I want to talk about today:
can there be a bounce ?
can perturbations produced before the bounce pass thru ?


Contraction and Crunch:
Building Block Concepts
reversal
scale-invariance
negligible T & ρ at bounce
ultralocality:
homogeneous & isotropic collapse
passage of pert's thru bounce
w > 1
during contraction
Z2 orbifold


reversal from expansion to contraction
in a flat universe
$H^2 = \frac{1}{3}(\frac{1}{2}\dot{\phi}^2 + V)$
reversal → $H = 0$ → V < 0
$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} > 1$
V
φ


scale-invariance
approach: quantum fluct. exit horizon & re-enter later
$\varepsilon \equiv \frac{3}{2}(1+w)$
$a(t) \sim t^{\frac{1}{\varepsilon}} \sim (H^{-1})^{\frac{1}{\varepsilon}}$
expanding
contracting
ε < 1
ε > 1
$n_s \approx 1:$
ε << 1
ε >> 1
$n_s - 1 = -2\varepsilon + \frac{d \ln \varepsilon}{dN}$
$n_s - 1 = -\frac{2}{\varepsilon} - \frac{d \ln \varepsilon}{d N}$


scale-invariance
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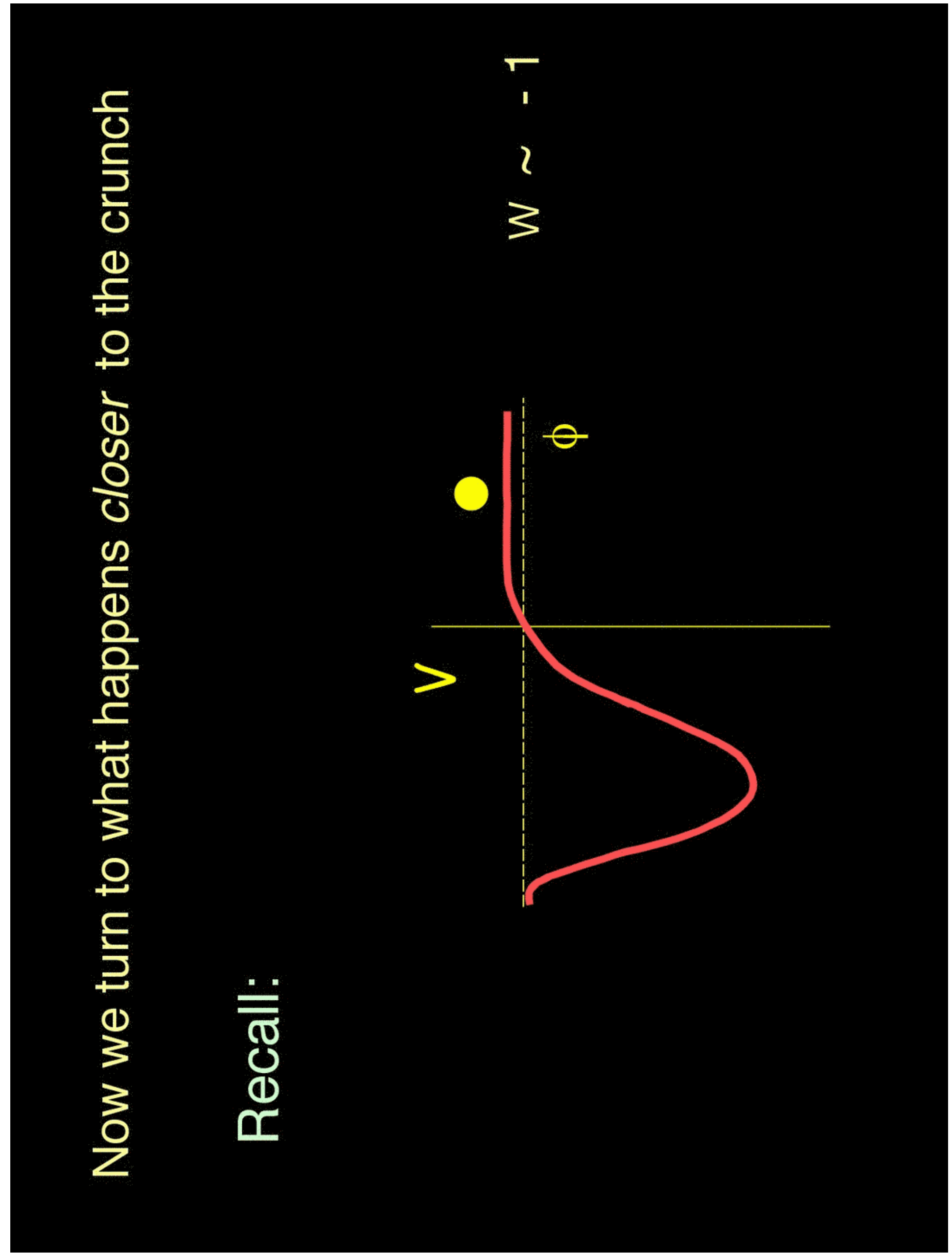
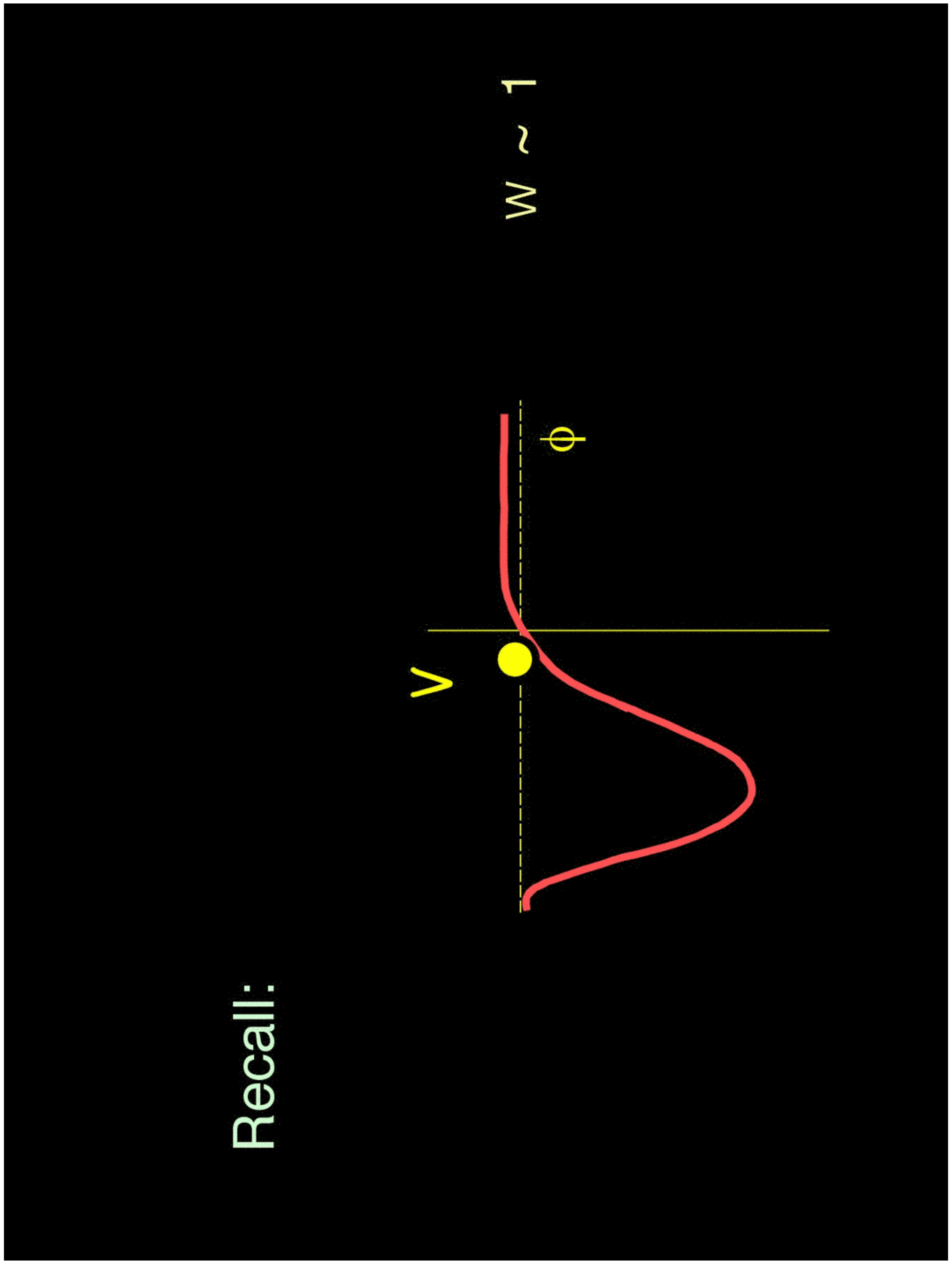
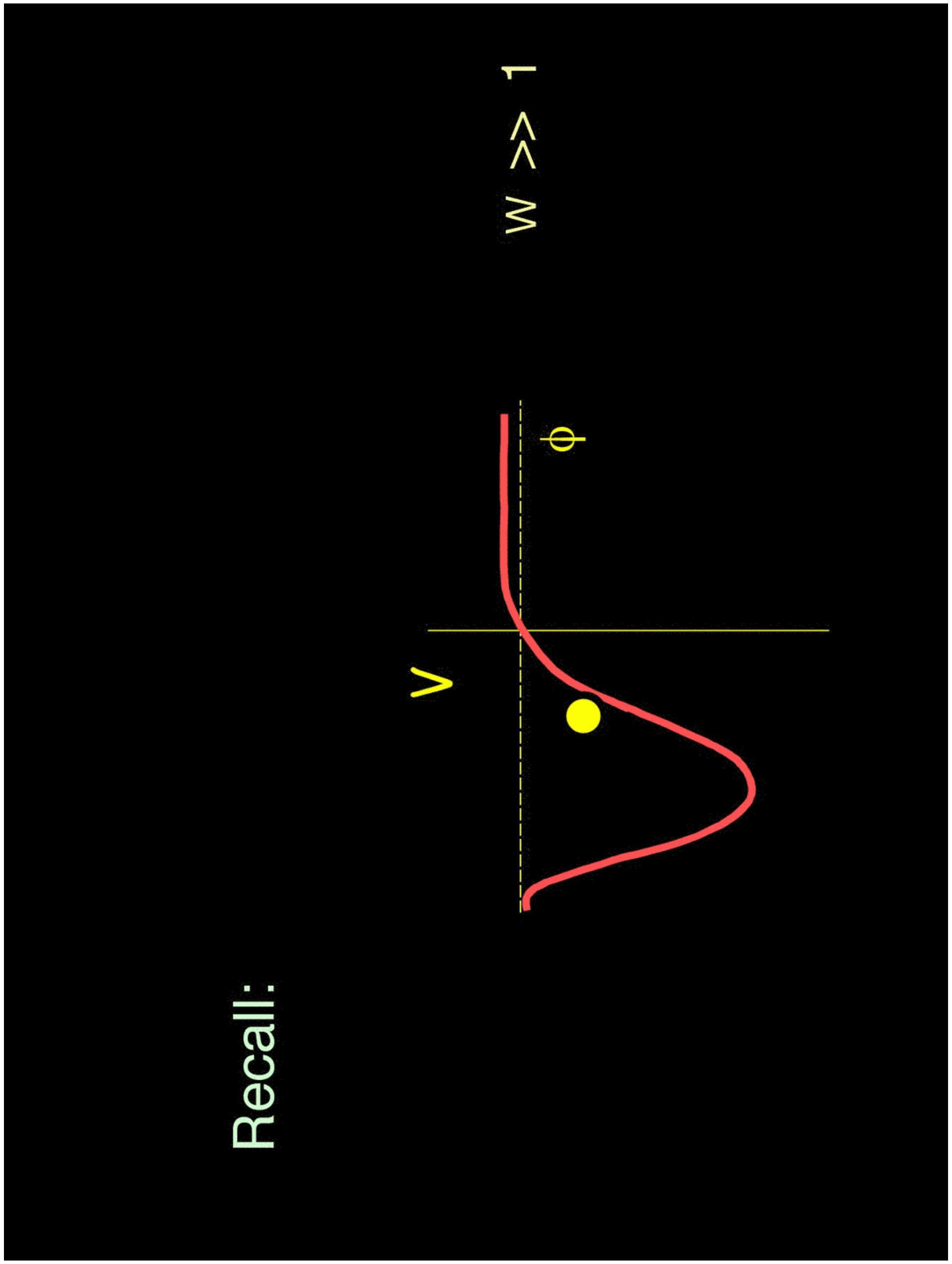
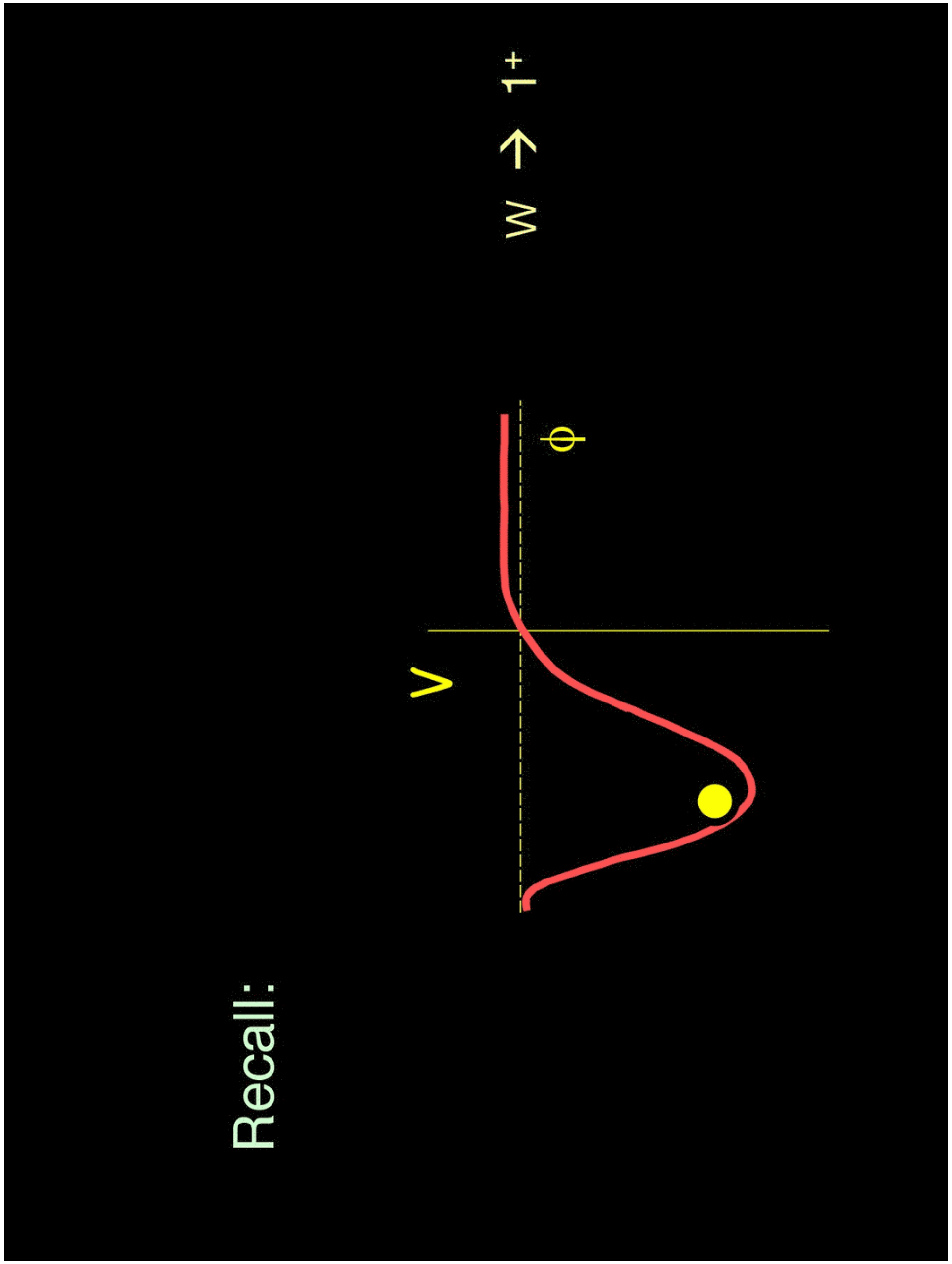
$\varepsilon \equiv \frac{3}{2}(1+w)$
$a(t) \sim t^{\frac{1}{\varepsilon}} \sim (H^{-1})^{\frac{1}{\varepsilon}}$
expanding
contracting
ε < 1
ε > 1
$n_s \approx 1:$
ε << 1
ε >> 1
$n_s - 1 = -2\varepsilon + \frac{d \ln \varepsilon}{dN}$
"dual"
ε → 1/ ε
$n_s - 1 = -\frac{2}{\varepsilon} - \frac{d \ln \varepsilon}{d N}$

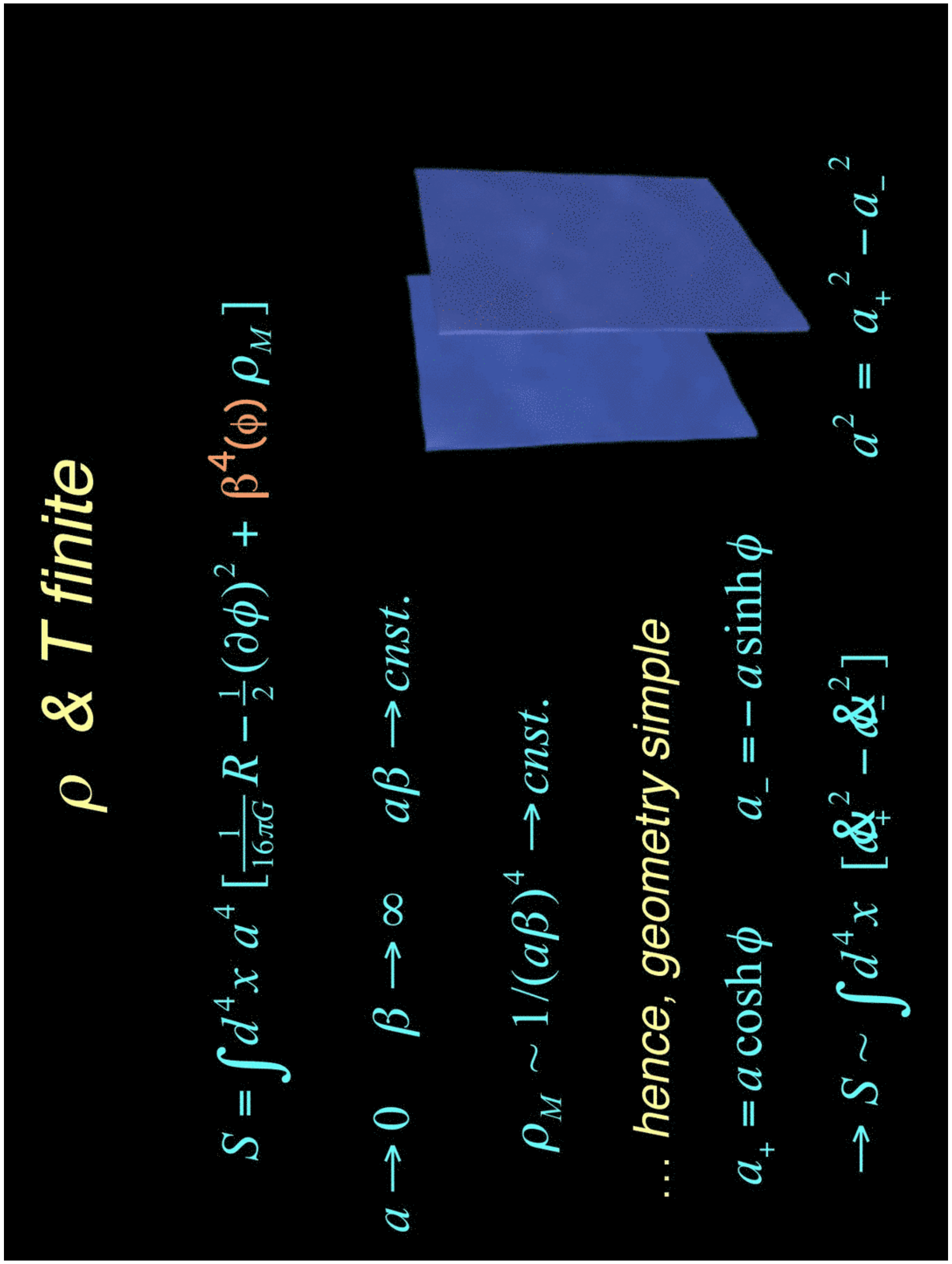

Now we turn to what happens *closer* to the crunch
Recall:
V
φ
W ~ -1


Recall:
V
ϕ
W ~ 1

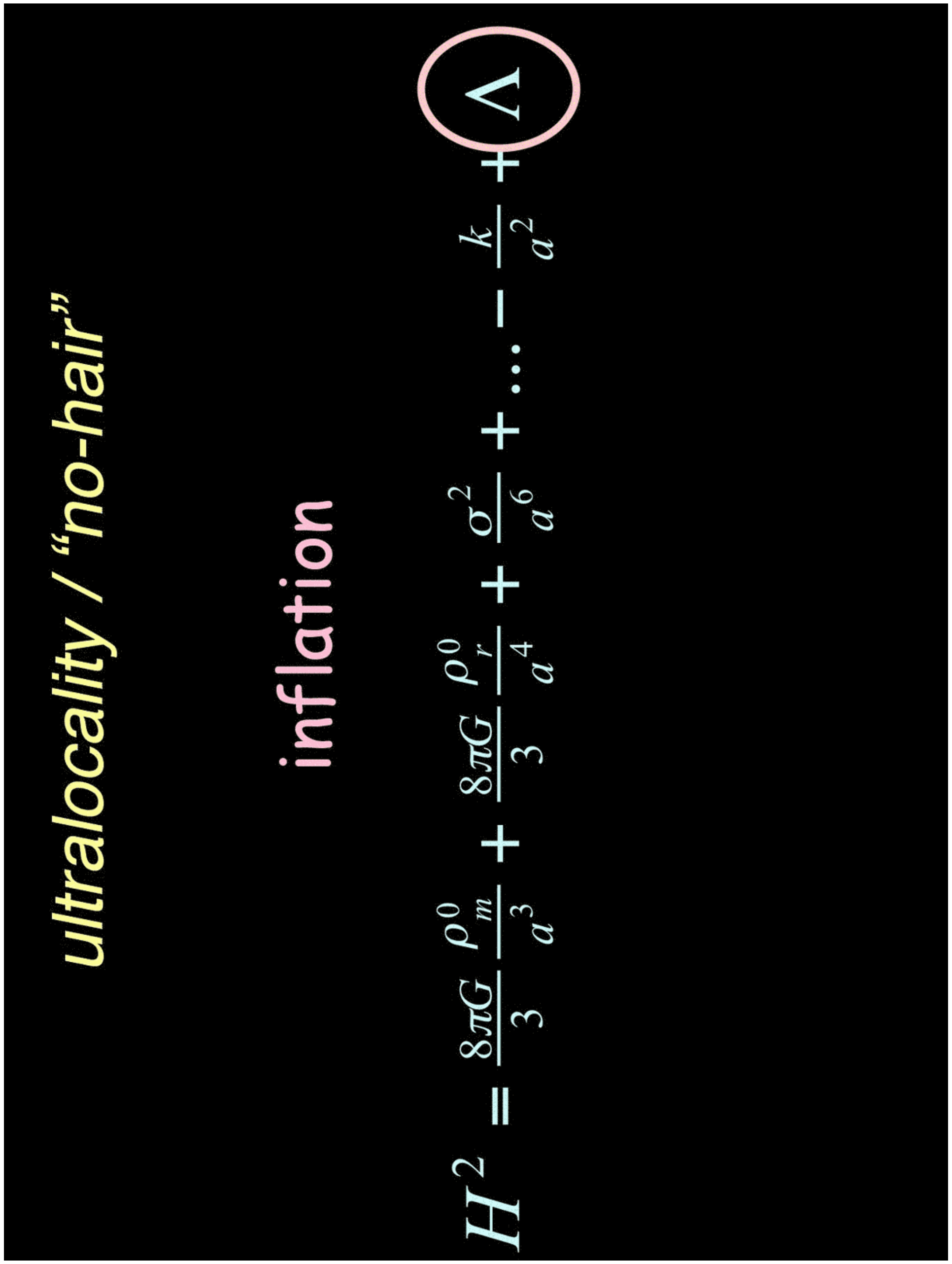

Recall:
V
ϕ
W >> 1

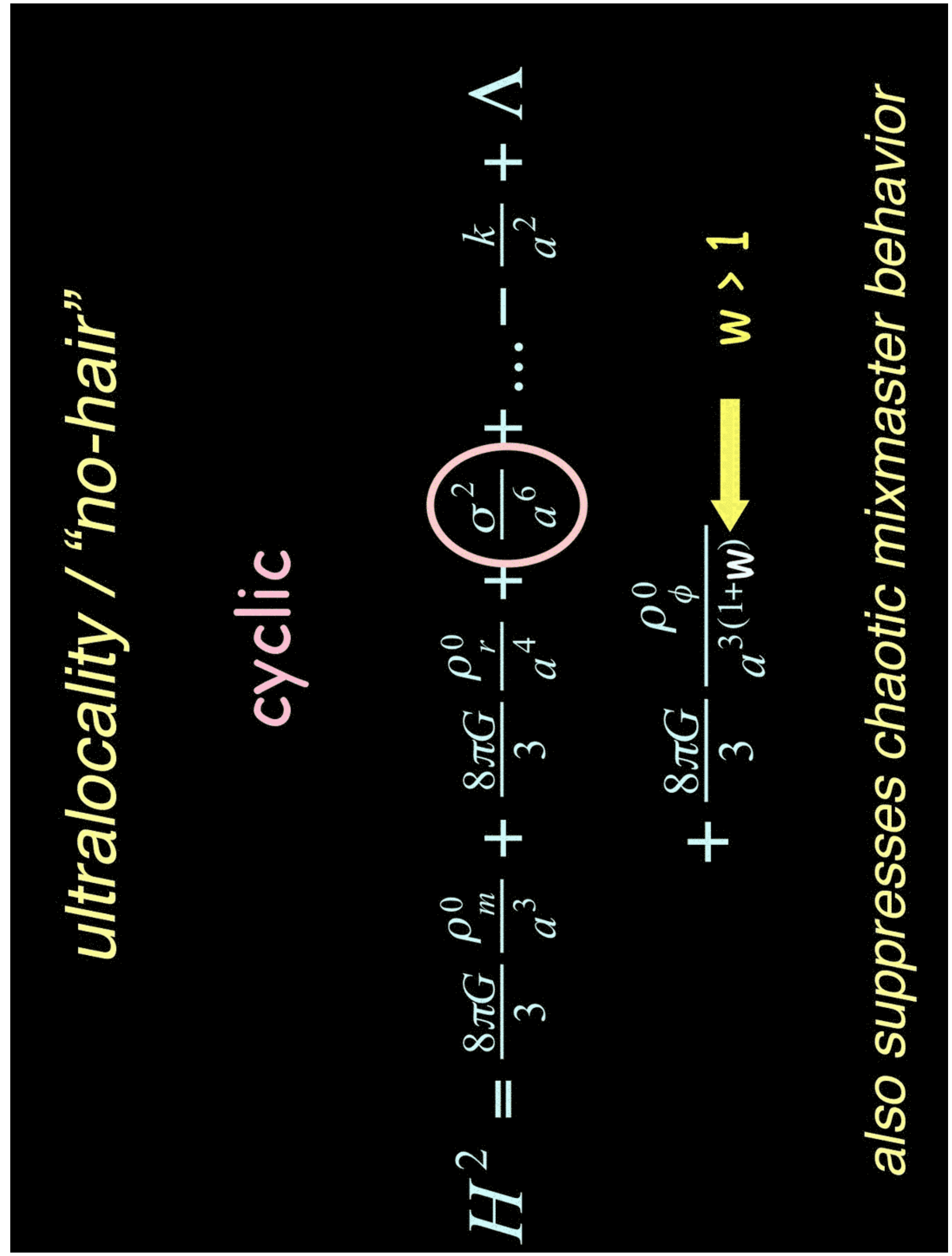


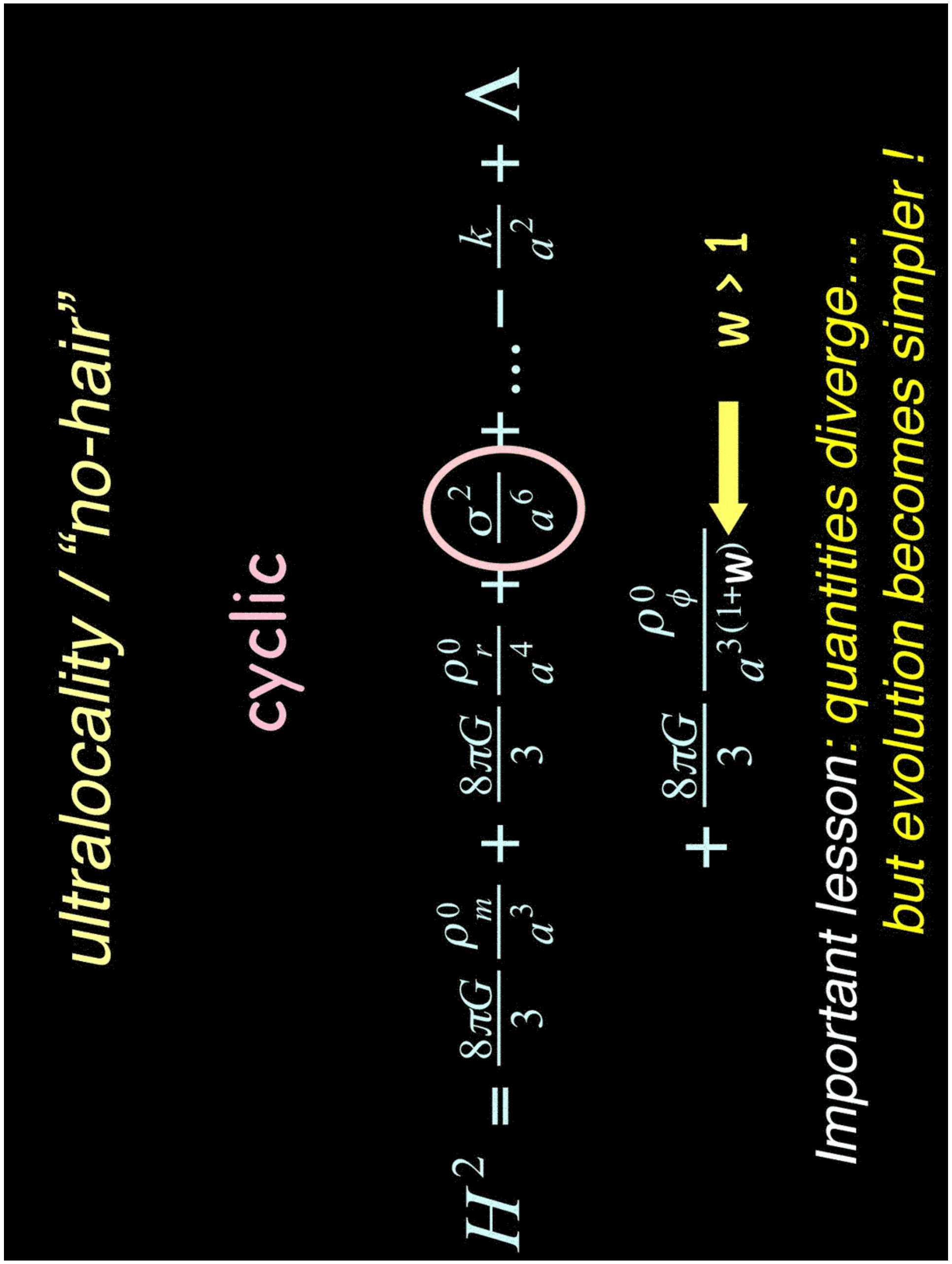
Recall:
V
φ
w → 1+



ρ & T finite
$S = \int d^4x\, a^4 \left[\frac{1}{16\pi G} R - \frac{1}{2}(\partial\phi)^2 + \beta^4(\phi)\, \rho_M \right]$
$a \to 0 \quad \beta \to \infty \quad a\beta \to cnst.$
$\rho_M \sim 1/(a\beta)^4 \to cnst.$
… hence, geometry simple
$a_+ = a\cosh\phi \quad a_- = -a\sinh\phi$
$\to S \sim \int d^4x\, [\dot{a}_+^2 - \dot{a}_-^2]$
$a^2 = a_+^2 - a_-^2$


ultralocality / "no-hair"
inflation
$H^2 = \frac{8\pi G}{3}\frac{\rho_m^0}{a^3} + \frac{8\pi G}{3}\frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \ldots - \frac{k}{a^2} + \Lambda$


ultralocality / "no-hair"
cyclic
$H^2 = \frac{8\pi G}{3}\frac{\rho_m^0}{a^3} + \frac{8\pi G}{3}\frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \ldots - \frac{k}{a^2} + \Lambda$
$+ \frac{8\pi G}{3}\frac{\rho_\phi^0}{a^{3(1+w)}}$
w > 1
also suppresses chaotic mixmaster behavior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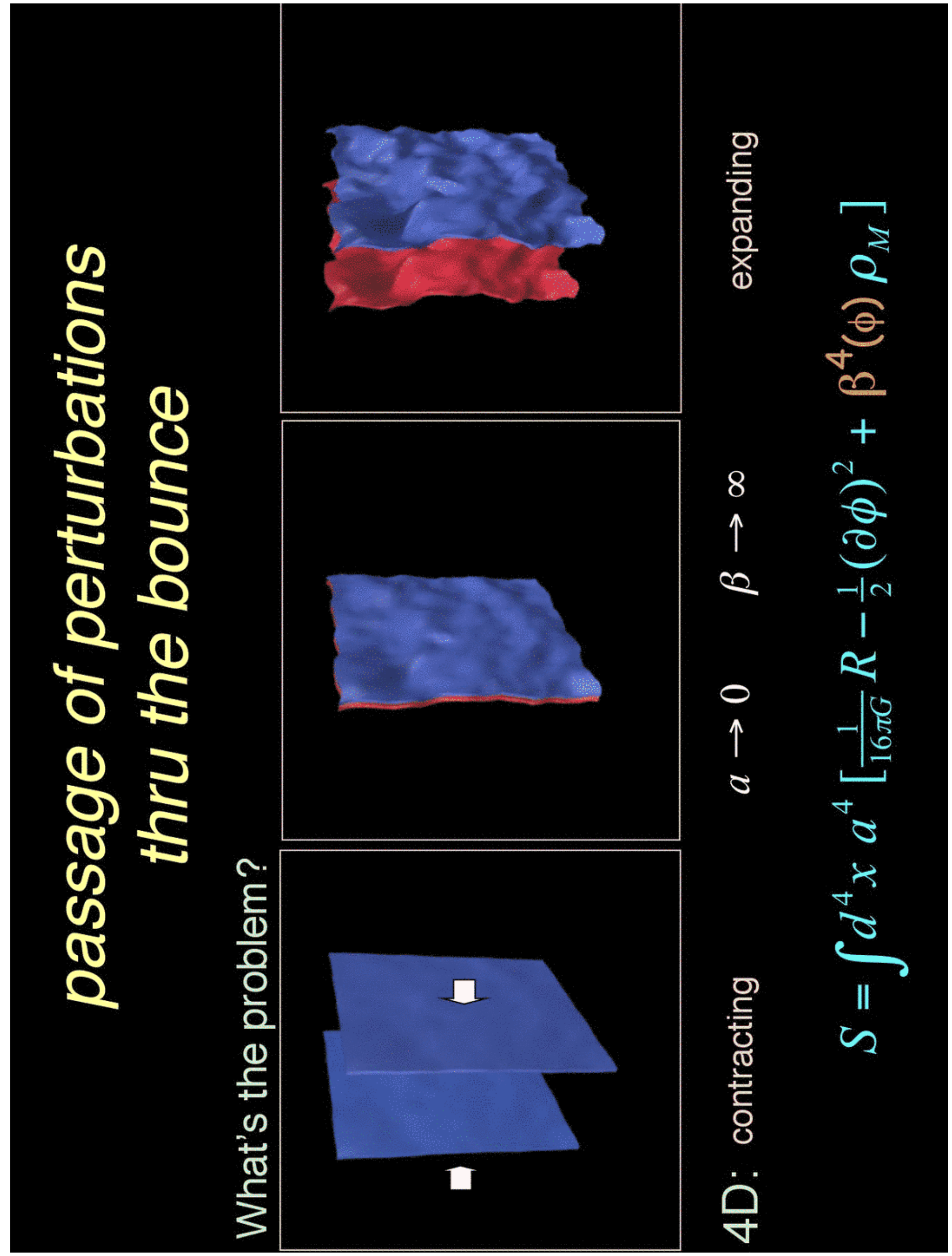
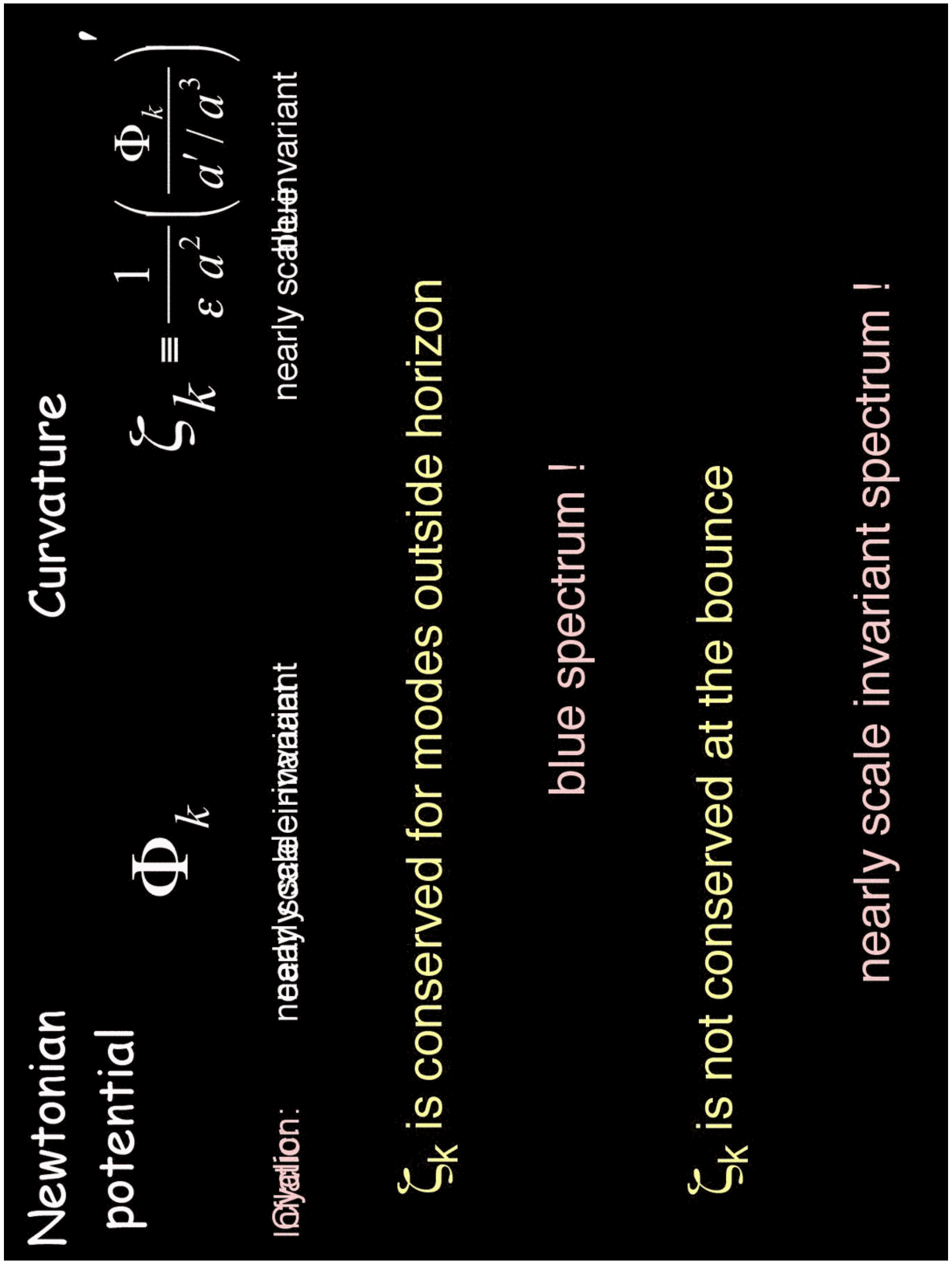
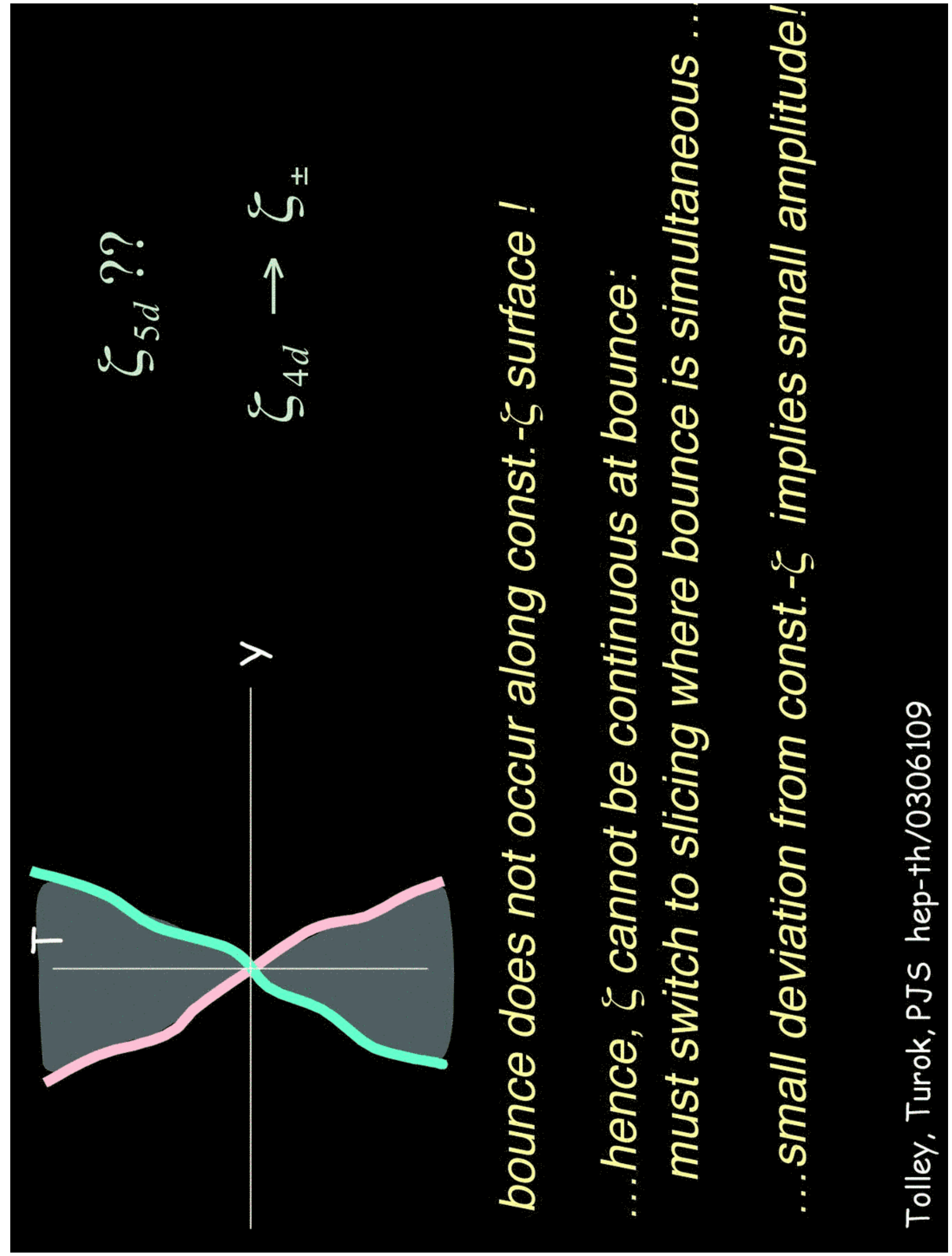
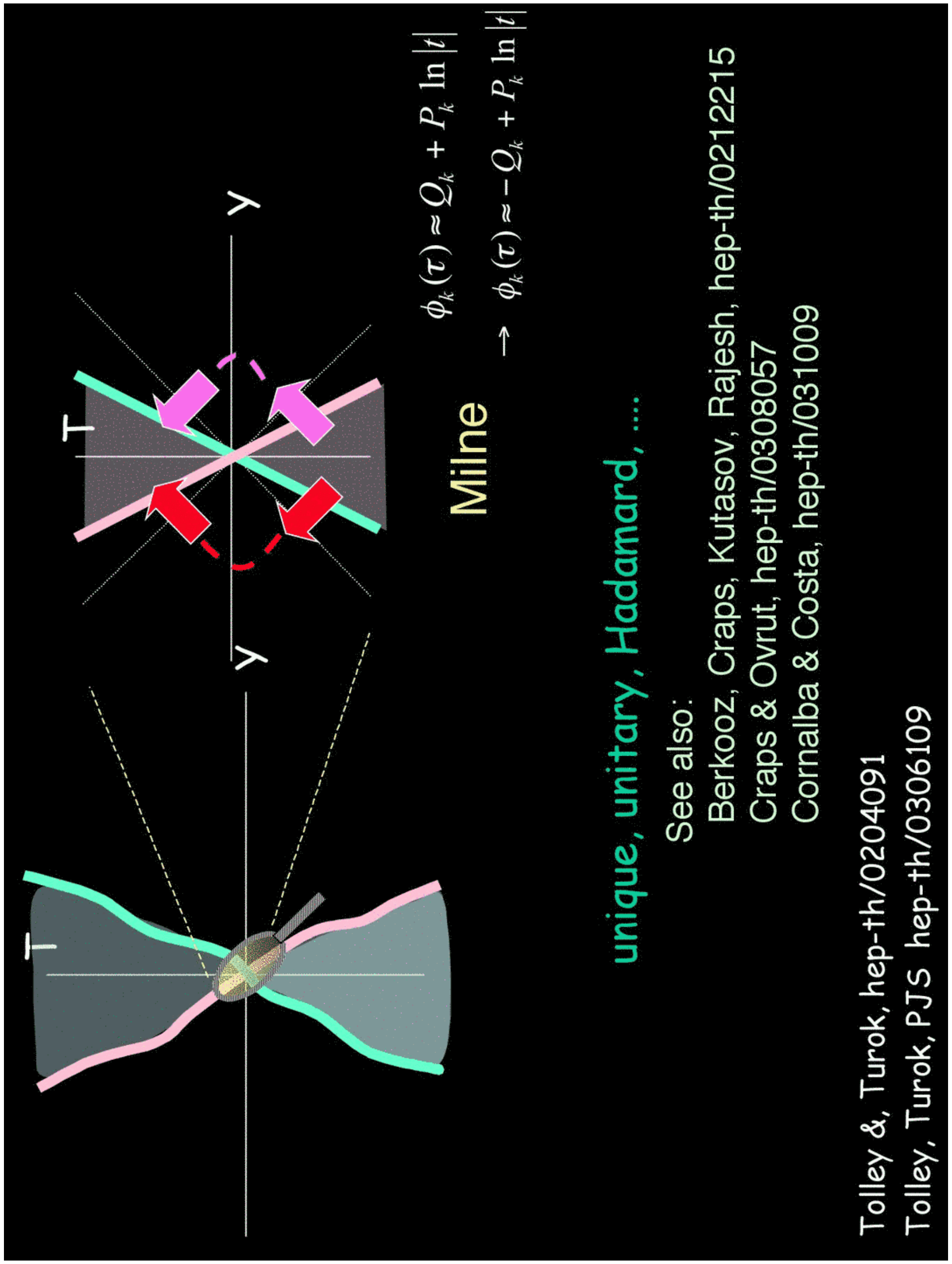
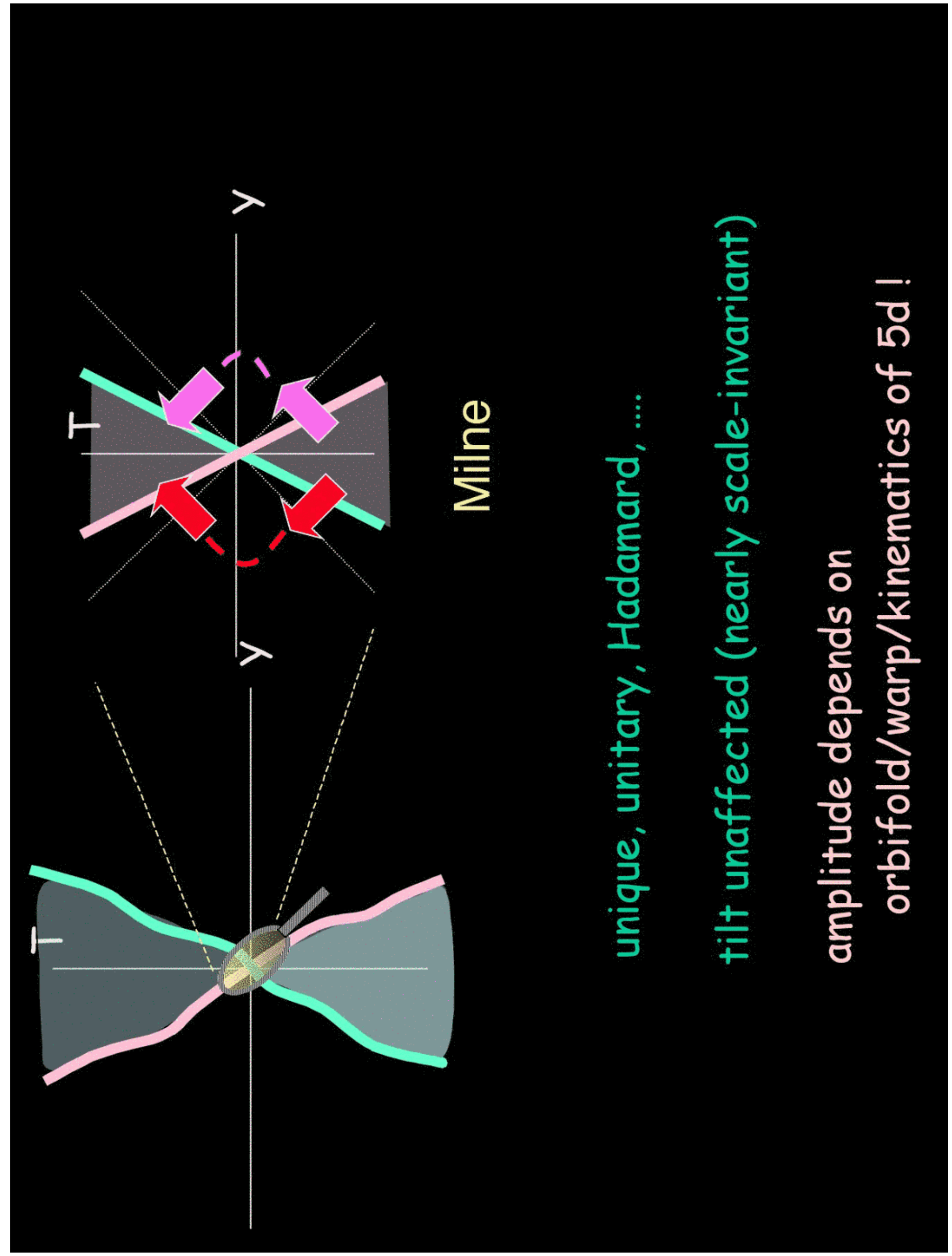
$H^2 = \frac{8\pi G}{3}\frac{\rho_m^0}{a^3} + \frac{8\pi G}{3}\frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \ldots - \frac{k}{a^2} + \Lambda$
$+ \frac{8\pi G}{3}\frac{\rho_\phi^0}{a^{3(1+w)}}$
w > 1
Important lesson: quantities diverge…
but evolution becomes simpler !

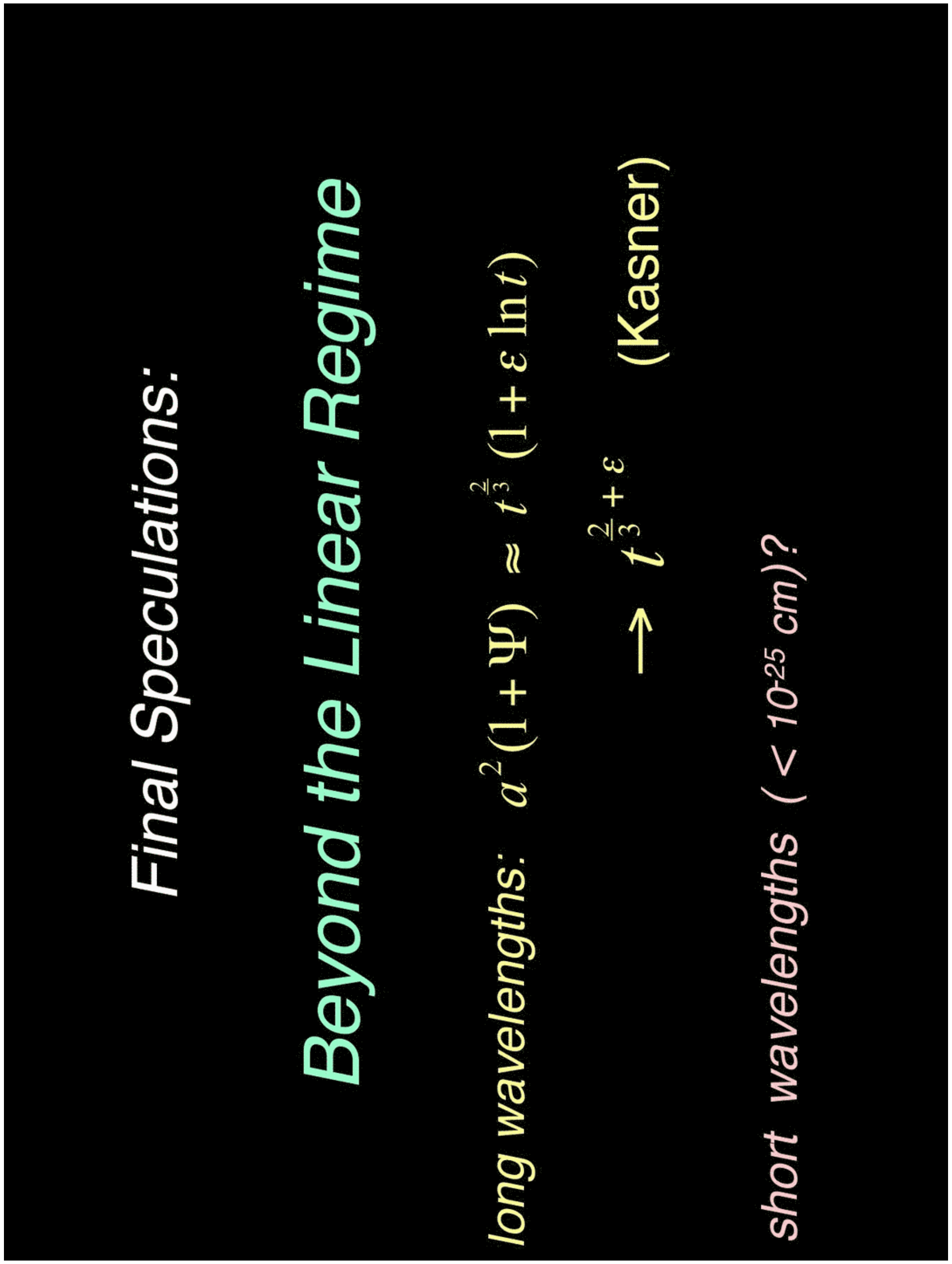

passage of perturbations
thru the bounce
What's the problem?
4D: contracting
$a \to 0$
$\beta \to \infty$
expanding
$S = \int d^4x\, a^4 \left[\frac{1}{16\pi G} R - \frac{1}{2}(\partial\phi)^2 + \beta^4(\phi)\, \rho_M\right]$

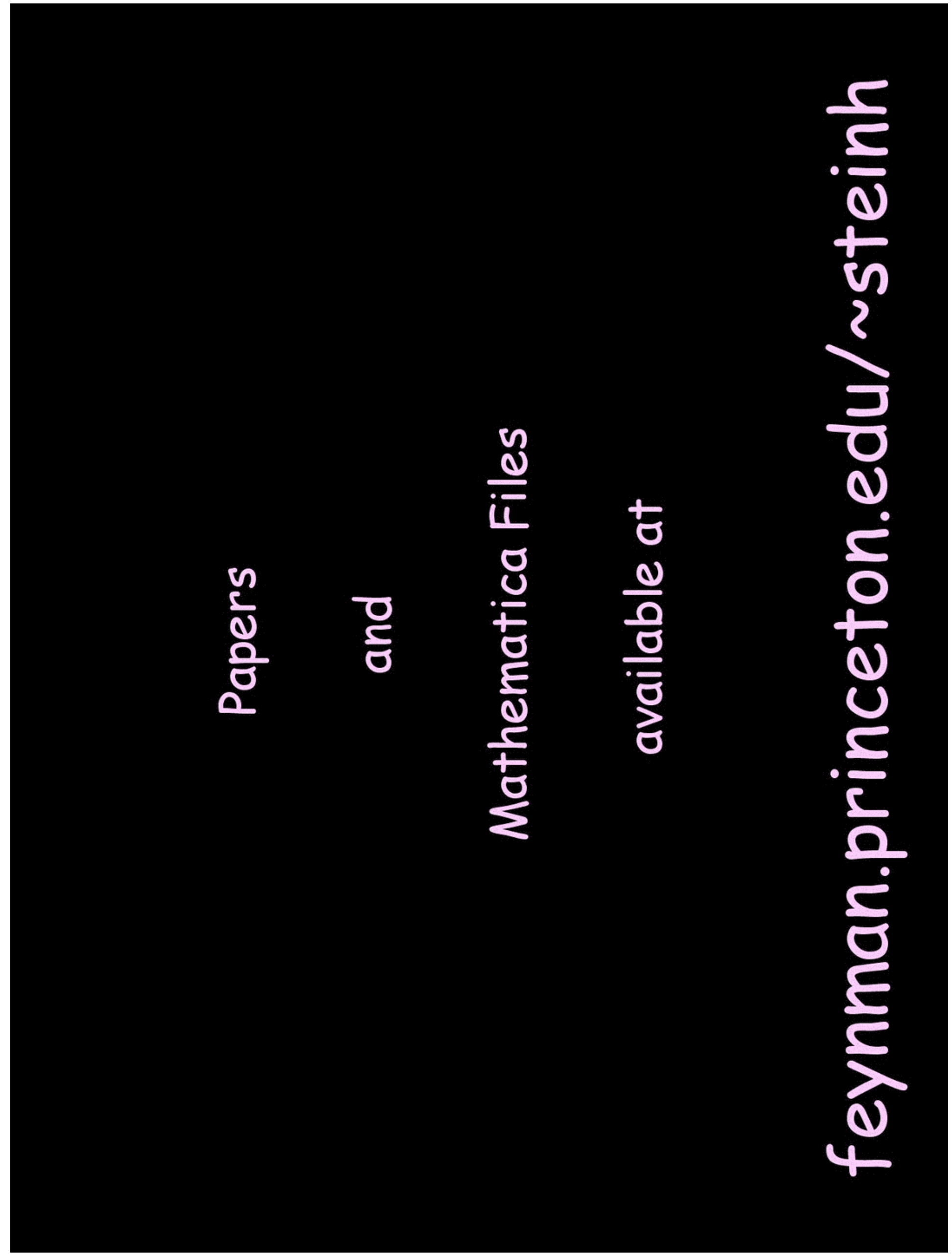

Newtonian potential
Φ_k
Curvature
$\zeta_k \equiv \frac{1}{\varepsilon\, a^2}\left(\frac{\Phi_k}{a'/a^3}\right)'$
ζ_k is conserved for modes outside horizon
blue spectrum !
ζ_k is not conserved at the bounce
nearly scale invariant spectrum !


ζ_{5d} ??
$\zeta_{4d} \rightarrow \zeta_{\pm}$
T
y
bounce does not occur along const.-ζ surface !
…hence, ζ cannot be continuous at bounce:
must switch to slicing where bounce is simultaneous …
…small deviation from const.-ζ implies small amplitude!
Tolley, Turok, PJS hep-th/0306109


T
y
T
y
Milne
$\phi_k(\tau) \approx Q_k + P_k \ln|t|$
$\rightarrow \phi_k(\tau) \approx -Q_k + P_k \ln|t|$
unique, unitary, Hadamard, ….
See also:
Berkooz, Craps, Kutasov, Rajesh, hep-th/0212215
Craps & Ovrut, hep-th/0308057
Cornalba & Costa, hep-th/031009
Tolley &, Turok, hep-th/0204091
Tolley, Turok, PJS hep-th/0306109


T
y
T
y
Milne
unique, unitary, Hadamard, ….
tilt unaffected (nearly scale-invariant)
amplitude depends on
orbifold/warp/kinematics of 5d !


Final Speculations:
Beyond the Linear Regime
long wavelengths: $a^2(1+\Psi) \approx t^{\frac{2}{3}}(1+\varepsilon \ln t)$
$\to t^{\frac{2}{3}+\varepsilon}$ (Kasner)
short wavelengths (< 10^{-25} cm)?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Mathematica Files
available at
feynman.princeton.edu/~steinh