The Phantom Bounce

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Katherine Freese
Michigan Center for Theoretical Physics
University of Michigan

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with:
Matthew Brown
William Kinney
(Univ. at Buffalo)

The Third Way

- Homogeneous and isotropic universe:
- Do we live in a special place?
- Two options discussed so far: special initial conditions or inflation.
- Third option: cyclicity
- Question: how can we live in a “medium” entropy universe? Need to reset by destroying the entropy created in each cycle. Our toy model considers violation of weak energy condition as mechanism to destroy black holes.
- Key Advantage: Testable in astrophysical data soon.

Oscillating Cosmologies

- The universe oscillates through a series of expansions and contractions. First proposed in the 1930's by Tolman.
- After an expanding phase, universe reaches "***turnaround***" (max expansion), then recollapses till "***bounce***" (smallest extent), then expands again.
- Problems of the original model:

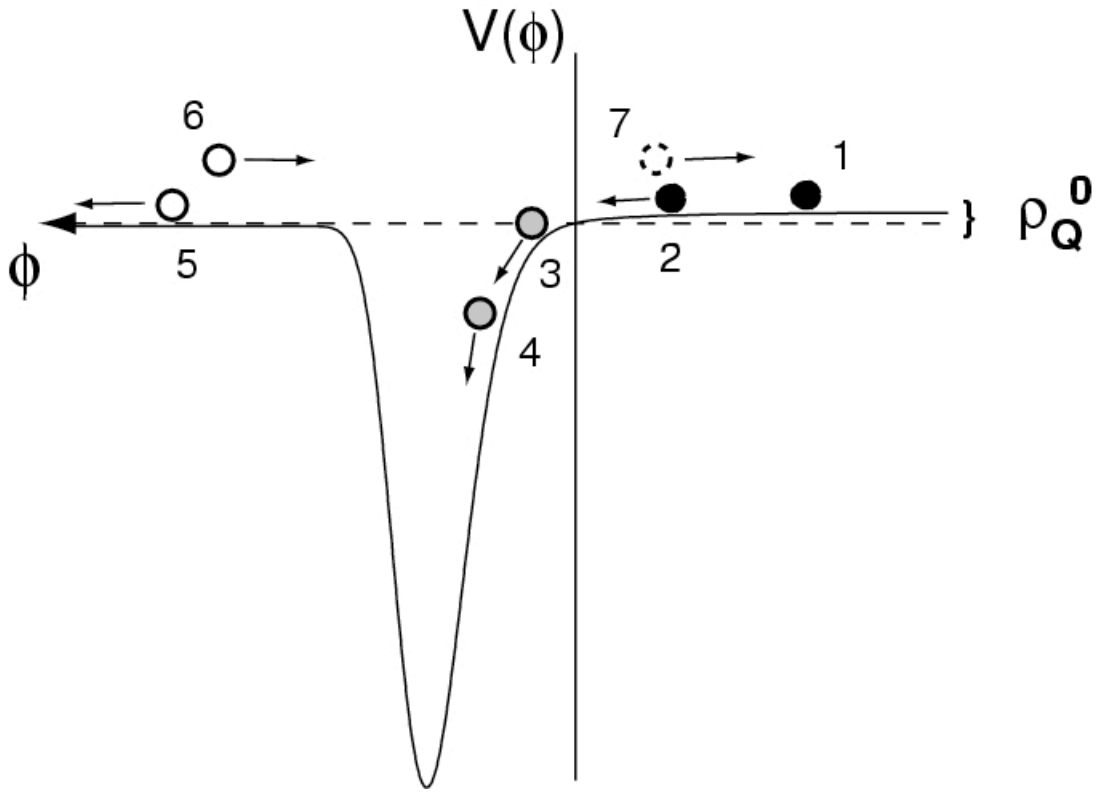
  1) Black holes cannot disappear due to Hawking area theorems, grow larger in each cycle, eventually fill the horizon and calculations fail.

  2) Lack of a mechanism for bounce and turnaround (n.b. closed universe could turn around, but discovery of accelerating universe removes possibility).

  3) Overall entropy production during each cycle implies start from a singularity

The Model of Steinhardt-Turok-Khoury

Oscillating brane causing alternating periods of inflation and ekpyrosis.



Our model: distinguishing features

- 3+1 dimensions (though braneworld motivated)
- Accelerating phase due to phantom energy characterized by component Q with equation of state

$$w_Q = \frac{p}{\rho} < -1$$

  tears apart all bound structures including BH
- Modifications to the Friedmann eqn. provide a mechanism for bounce and turnaround .

Modified Friedmann Equation and the bouncing universe

Chung,Freese(2000)

Add a negative term to the R.H.S. of the Friedmann Eq.:

$$H^2 = \frac{8\Pi}{3M_{pl}^{\ 2}}[\rho - f(\rho)] \qquad e.g. \qquad H^2 = \frac{8\pi}{3M_p^2}\left[\rho - \frac{\rho^2}{2|\sigma|}\right]$$

The universe bounces at high density:

$$H = 0 \;\Rightarrow\; \rho_{\rm bounce} = 2\,|\sigma|$$

("Natural" value from Randall-Sundrum-like models: $\sigma = M_p$)

General case: $(\mathrm{TeV})^4 < |\sigma| < M_p^4$

Braneworld model

Friedmann equation on the brane:

$$H^2 = \frac{\Lambda_4}{3} + \left(\frac{8\pi}{3M_p^2}\right)\rho + \epsilon\left(\frac{4\pi}{3M_5^3}\right)^2\rho^2 + \frac{C}{a^4}$$

Cosmological Constant

Brane tension

Dark radiation

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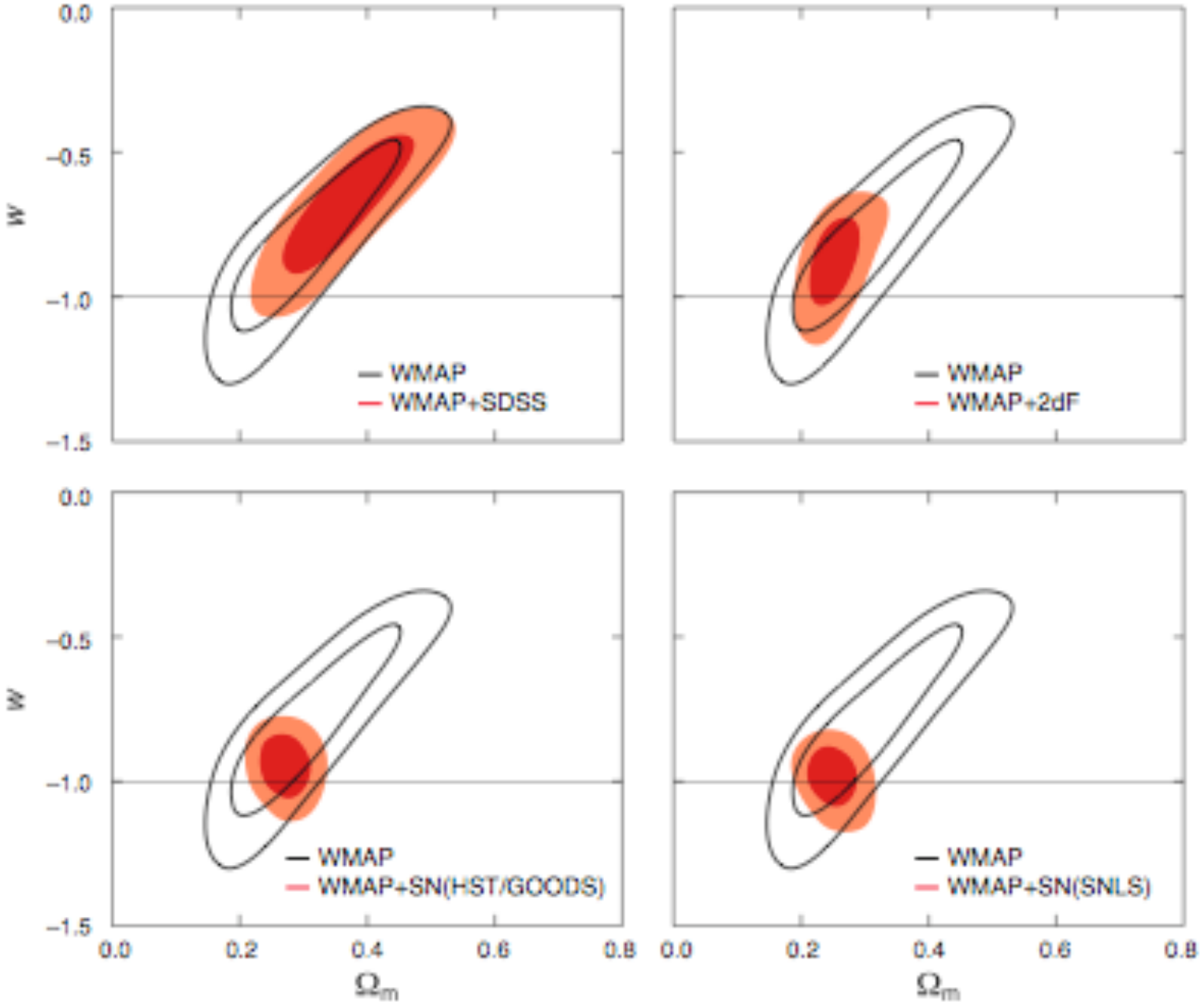
Generalized Randall-Sundrum solution: metric signature of extra dimension

(Shtanov & Sahni, gr-qc/0208047)

$$\epsilon < 0 \;\Rightarrow\; H^2 = \frac{8\pi}{3M_p^2}\left[\rho - \frac{\rho^2}{2|\sigma|}\right]$$

Dark Energy Equation of State: WMAP limits



(Spergel, et. al., astro-ph/0603449)

Phantom Energy

Observation does not rule out equation of state w < -1!

(Caldwell, astro-ph/9908168)

Phantom energy produces a runaway (i.e. superexponential) acceleration:

$$\frac{d\rho}{dt} + 3H(1+w)\rho = 0 \qquad \rho_Q \propto a^{-3(1+w_Q)}$$

$$w_Q < -1 \;\Rightarrow\; \frac{d\rho}{da} > 0$$

Energy density increases with expansion!

Cosmic Doomsday?

Phantom-dominated cosmologies have a singularity at late time: the Big Rip. Galaxies, planets, atoms, are all torn apart after finite time.

(Caldwell & Kamionkowski, astro-ph/0302506)

(This is in addition to other pathologies like an unstable vacuum and violation of the dominant energy condition!)

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Modified Friedmann Equation:

$$H^2 = \frac{8\pi}{3M_p^2}\left[\rho - \frac{\rho^2}{2|\sigma|}\right] \qquad \rho_Q \propto a^{-3(1+w_Q)}$$

No Big Rip! The universe "bounces" at both early and late times.

The Phantom Bounce

$$H^2 = \frac{8\pi}{3M_p^2}\left[\rho - \frac{\rho^2}{2|\sigma|}\right]$$

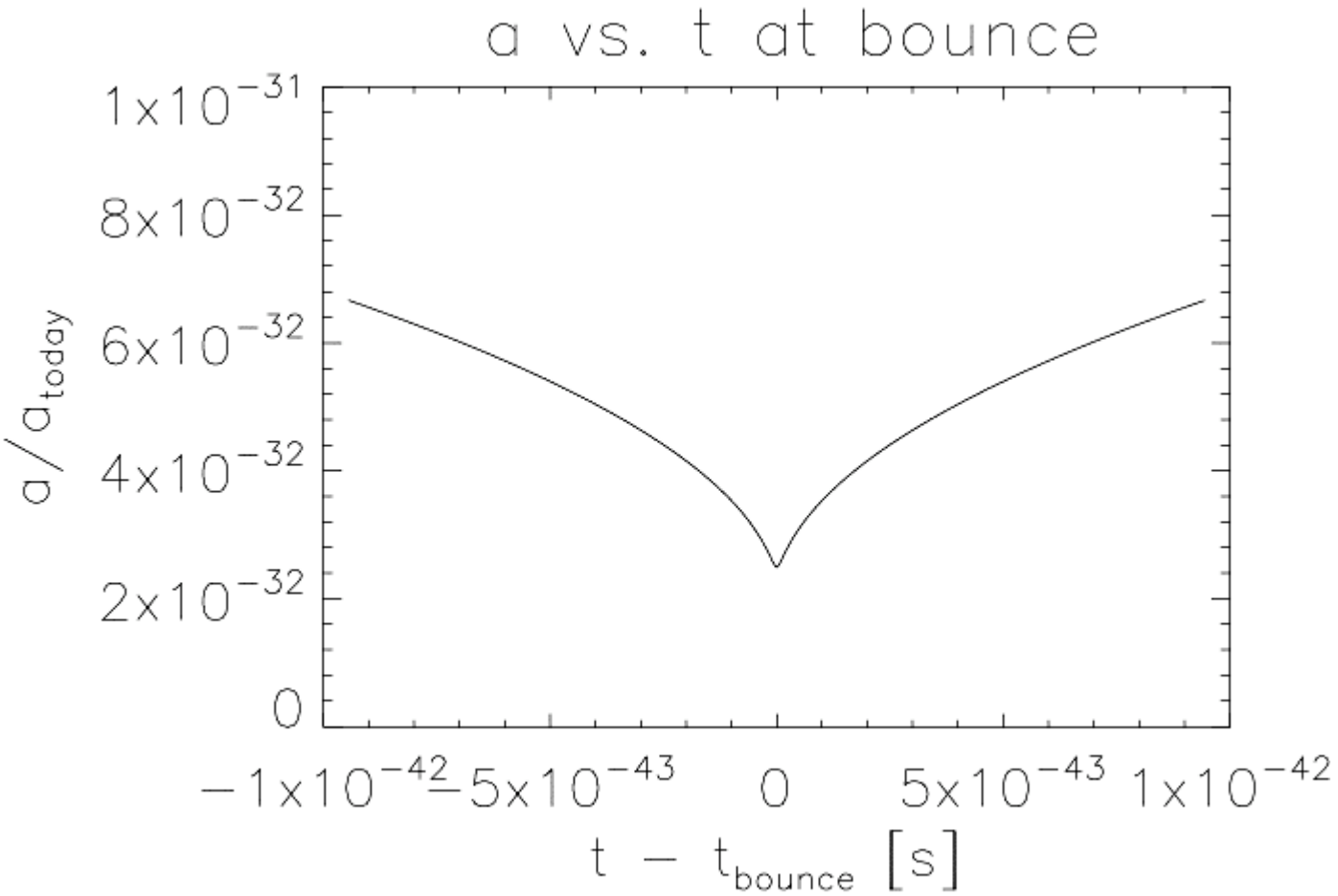
Small scale factor: $a \to 0 \quad \rho_R \to \infty$

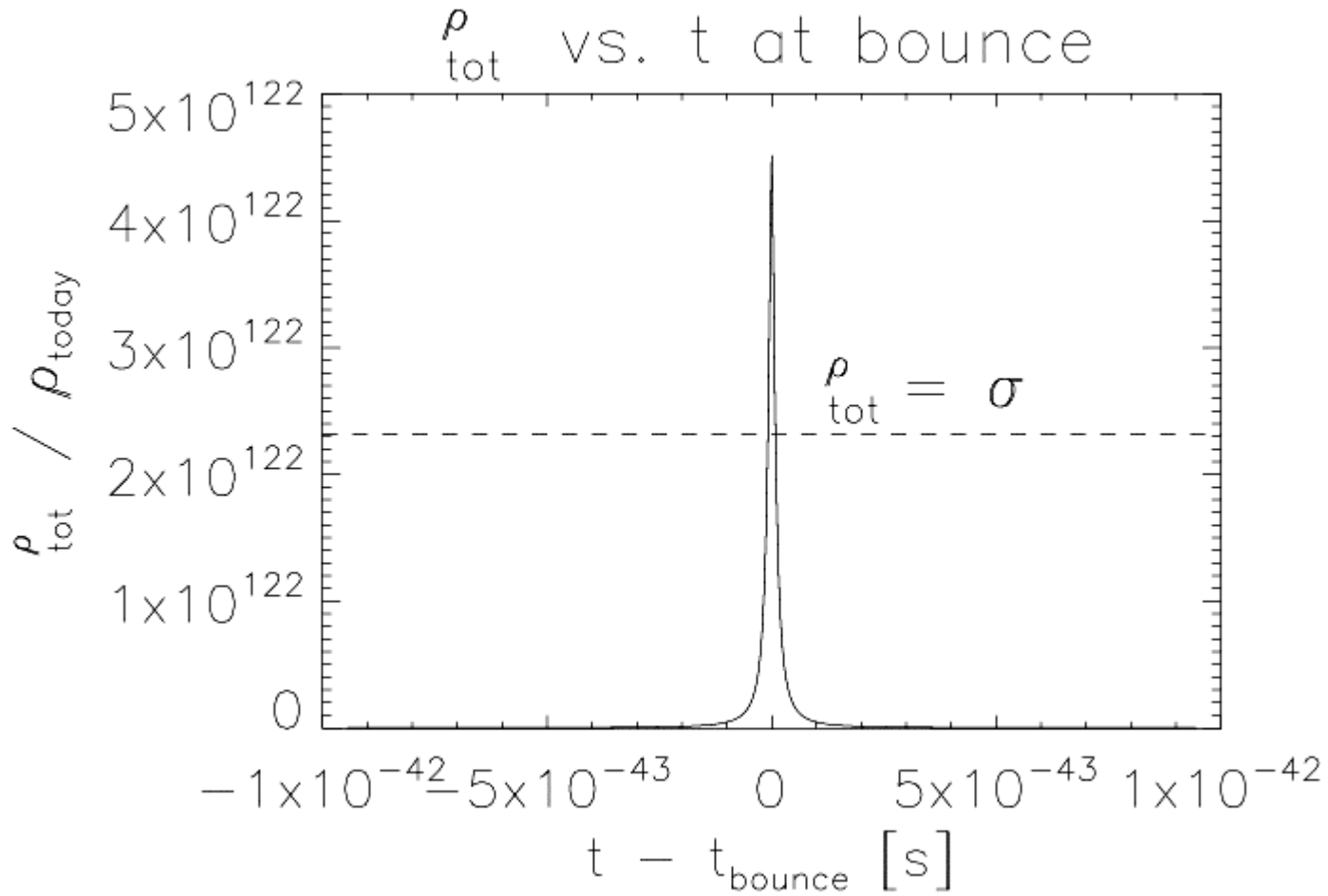
$$\rho_R = 2|\sigma| \Rightarrow H = 0$$ "bounce"

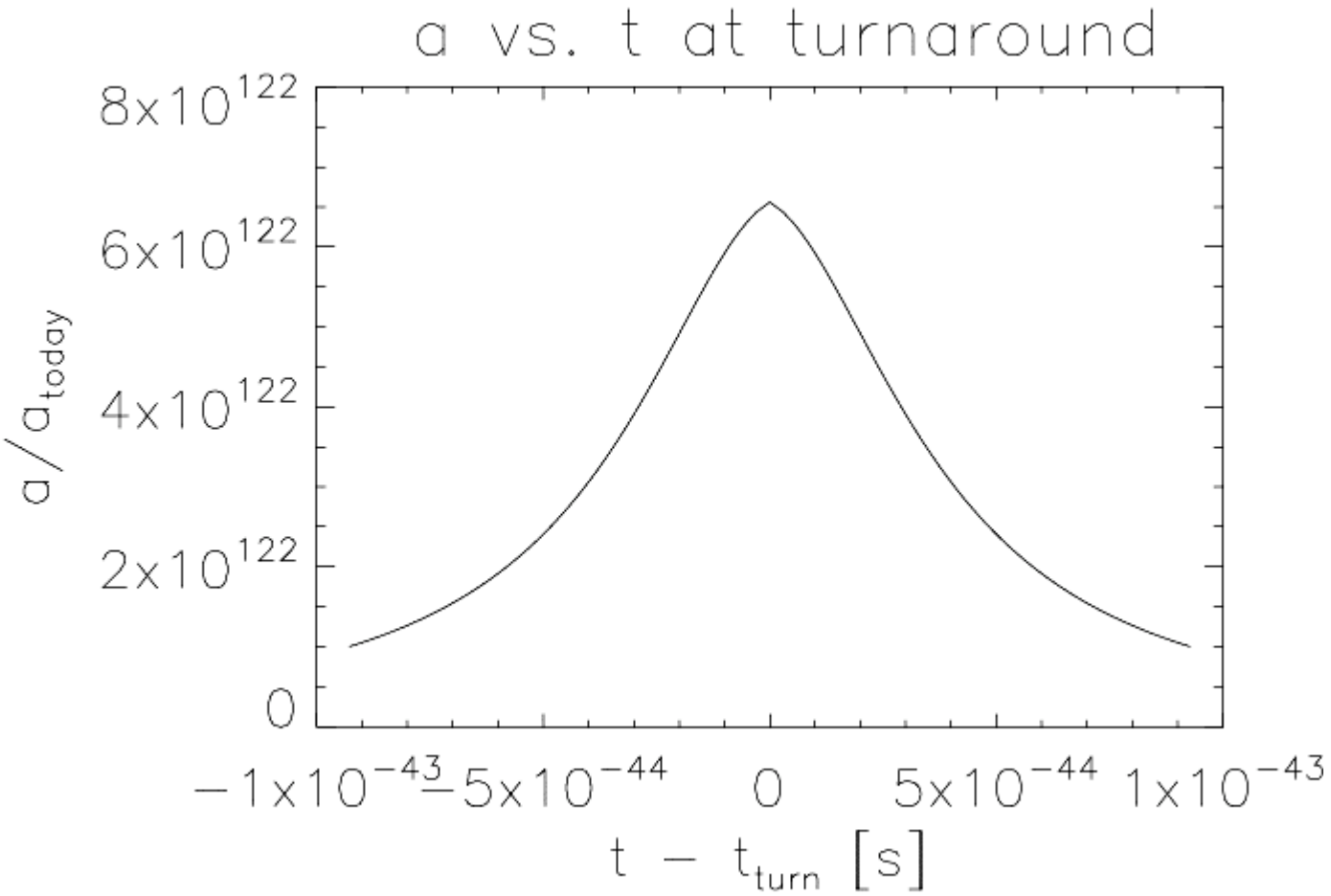
Large scale factor: $a \to \infty \quad \rho_Q \to \infty$

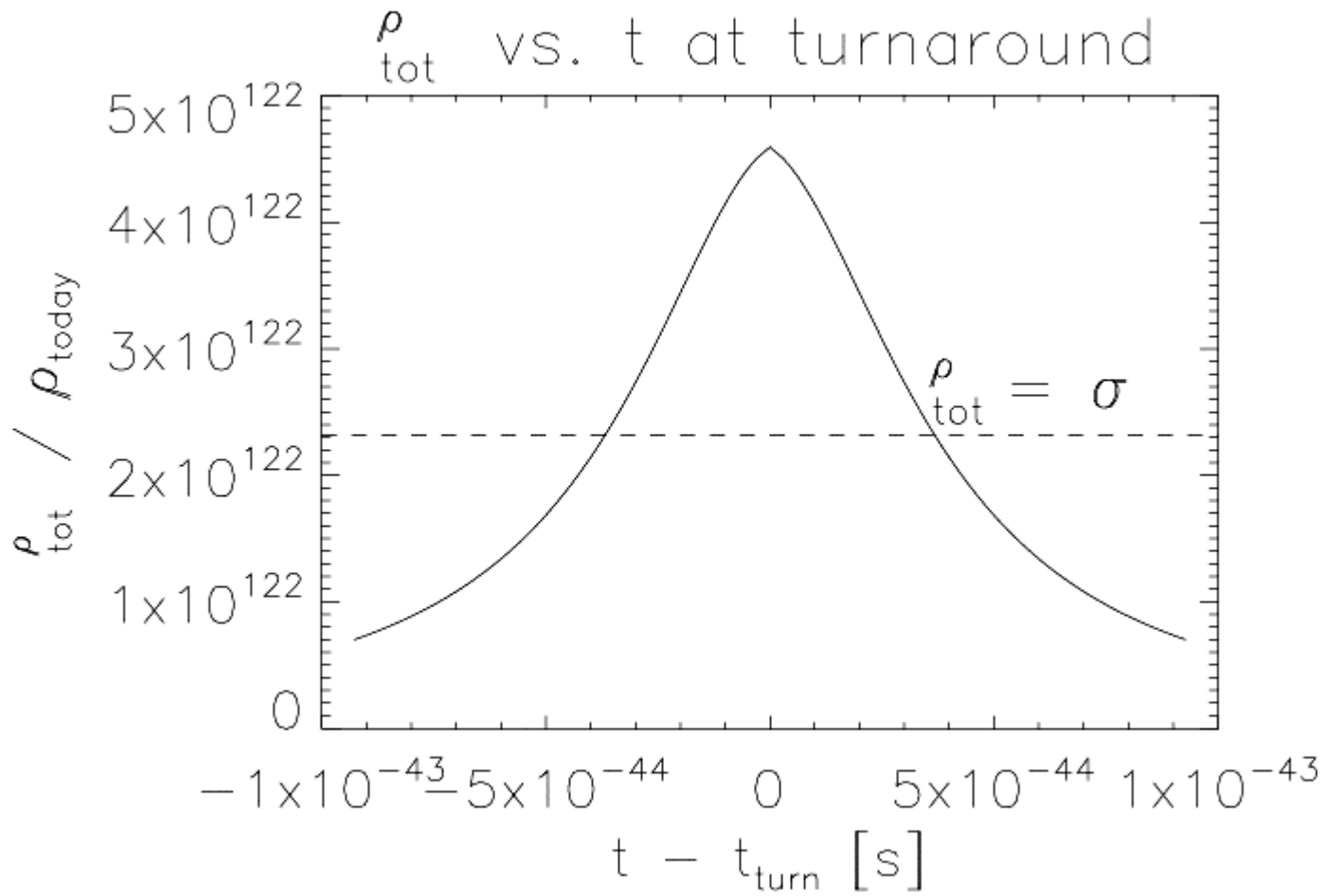
$$\rho_Q = 2|\sigma| \Rightarrow H = 0$$ "turnaround"

The same physics that causes the "bounce" at small scale factor causes the "turnaround" at large scale factor. **Nonsingular evolution!**


a vs. t at bounce
1x10^-31
8x10^-32
6x10^-32
4x10^-32
2x10^-32
0
a/a_today
-1x10^-42
-5x10^-43
0
5x10^-43
1x10^-42
t - t_bounce [s]


ρ tot vs. t at bounce
5x10^122
4x10^122
3x10^122
2x10^122
1x10^122
0
ρ tot / ρ today
ρ tot = σ
−1x10^−42
−5x10^−43
0
5x10^−43
1x10^−42
t − t bounce [s]


a vs. t at turnaround
8x10^122
6x10^122
4x10^122
2x10^122
0
a / a_today
−1x10^−43
−5x10^−44
0
5x10^−44
1x10^−43
t − t_turn [s]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t − t turn [s]

Destruction of Black Holes

Hawking area theorems break down for *w < -1*: Black Holes can be destroyed in Phantom cosmologies!

Davies, Annales Poincare Phys. Theor. **49**, 297 (1998)

Babichev, et al. gr-qc/0402089.

Source for the gravitational potential in GR: $\rho + 3p$

An object of radius R and mass M is pulled apart when:

$$-\frac{4\pi}{3}(\rho + 3p)R^3 \sim M$$

Destruction of Black Holes

Condition for the destruction of Black Holes of mass M:

$$\rho_{BH} \sim M_p^4 \left(\frac{M_p}{M}\right)^2 \frac{3}{32\pi} \frac{1}{|1+3w_Q|}$$

smaller black holes are destroyed later!

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Example: $w_Q = -3$

$$M = 10^6 M_{\rm sun} \longrightarrow \rho_{BH} \sim 10^{-90} M_p^4$$

$$M \sim M_p \longrightarrow \rho_{BH} = 10^{-2} M_p$$

Planck mass BHs destroyed before Planck density

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Planck mass relics a dark matter candidate?

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- A new oscillating cosmology
- Modified Friedmann Equation + Phantom Energy
- Bounce/turnaround cyclic evolution
- Destruction of nonlinear structures (Black Holes)
- **Nonsingular evolution**

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Outstanding issues:

- Truly cyclic? Entropy destroyed in acc. phase but reintroduced in collapsing phase?
- Boundary conditions for perturbations (turnaround!)
- Structure formation in collapsing phase
- $a \to 1/a$ duality? (pre-Big Bang)

Our key ingredient is testable

- If upcoming observations discover that w<-1 the community may be forced to conclude that the weak energy condition is violated and will need to rethink assumptions.
- Phantom energy may be forced upon us, with the helpful consequence of permitting a "medium" entropy universe.