Cosmology on the Beach 2012

Cancun Iberostar, 16 January

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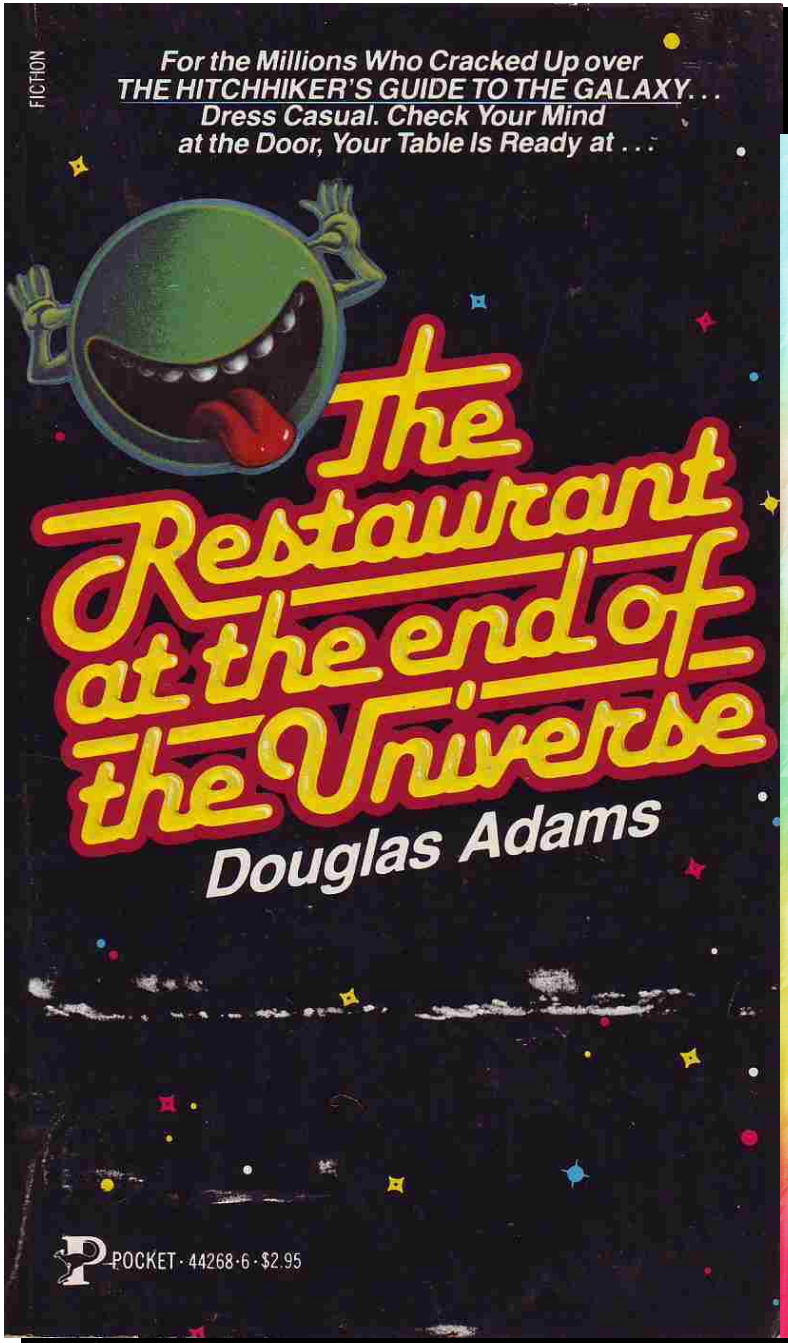
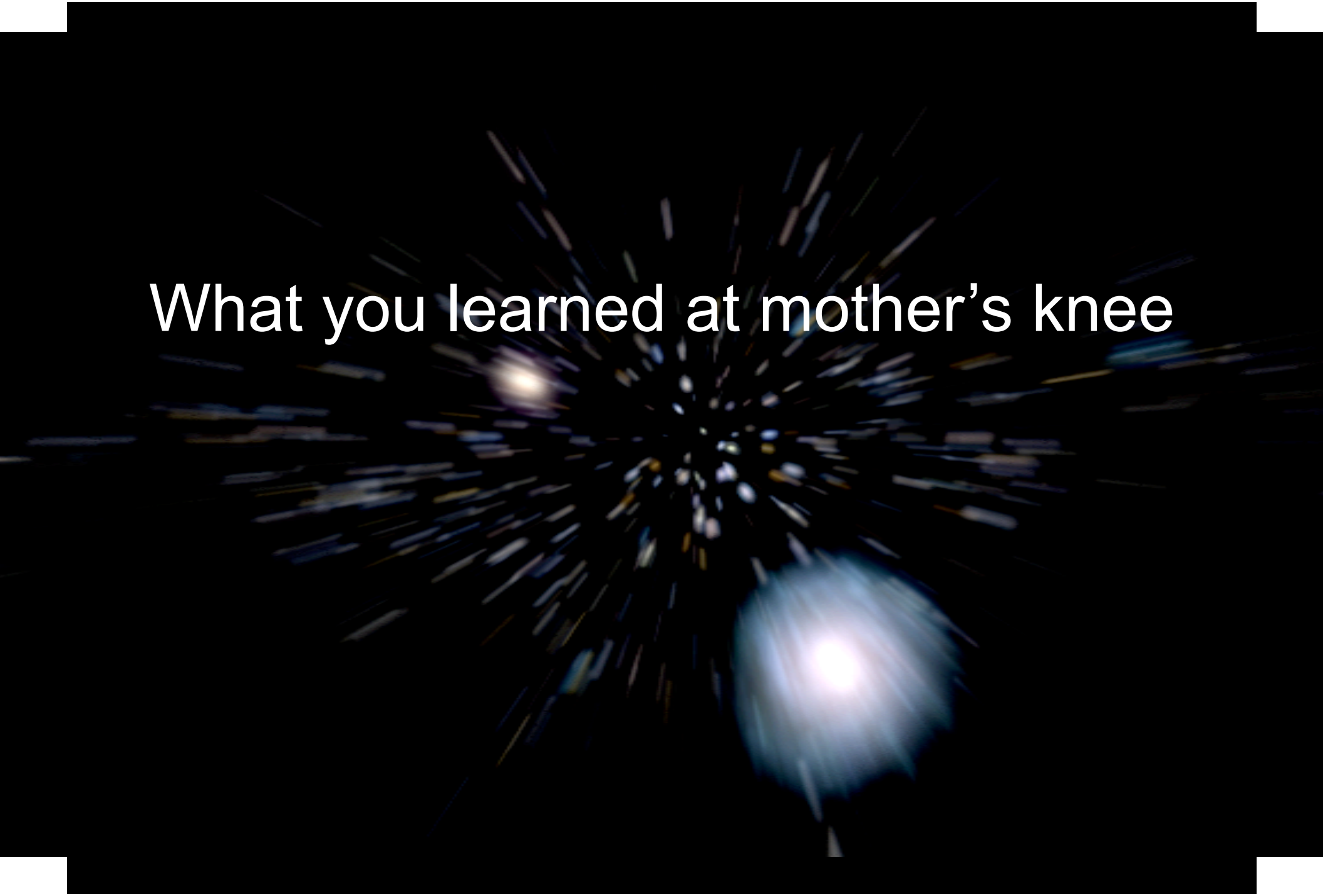
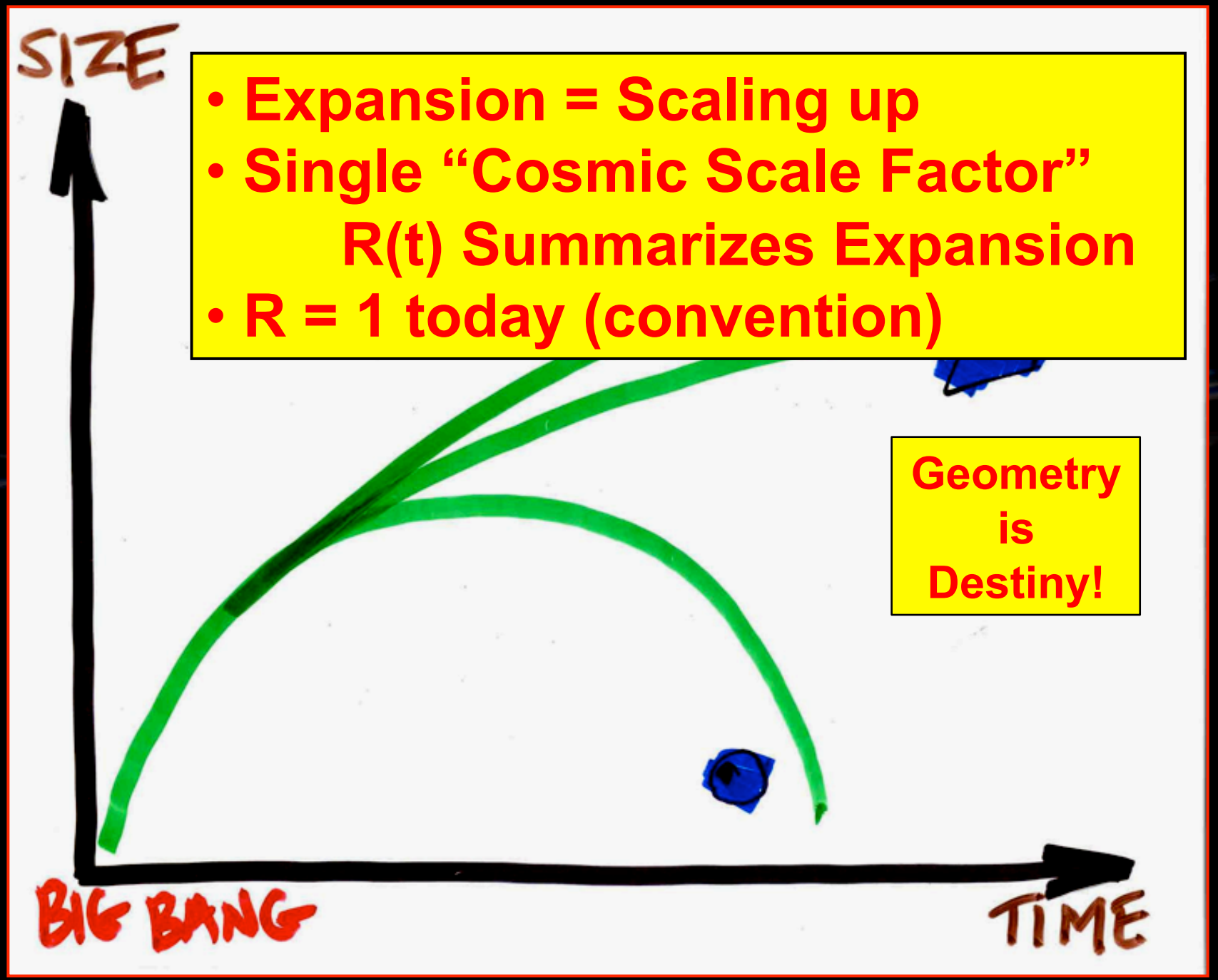
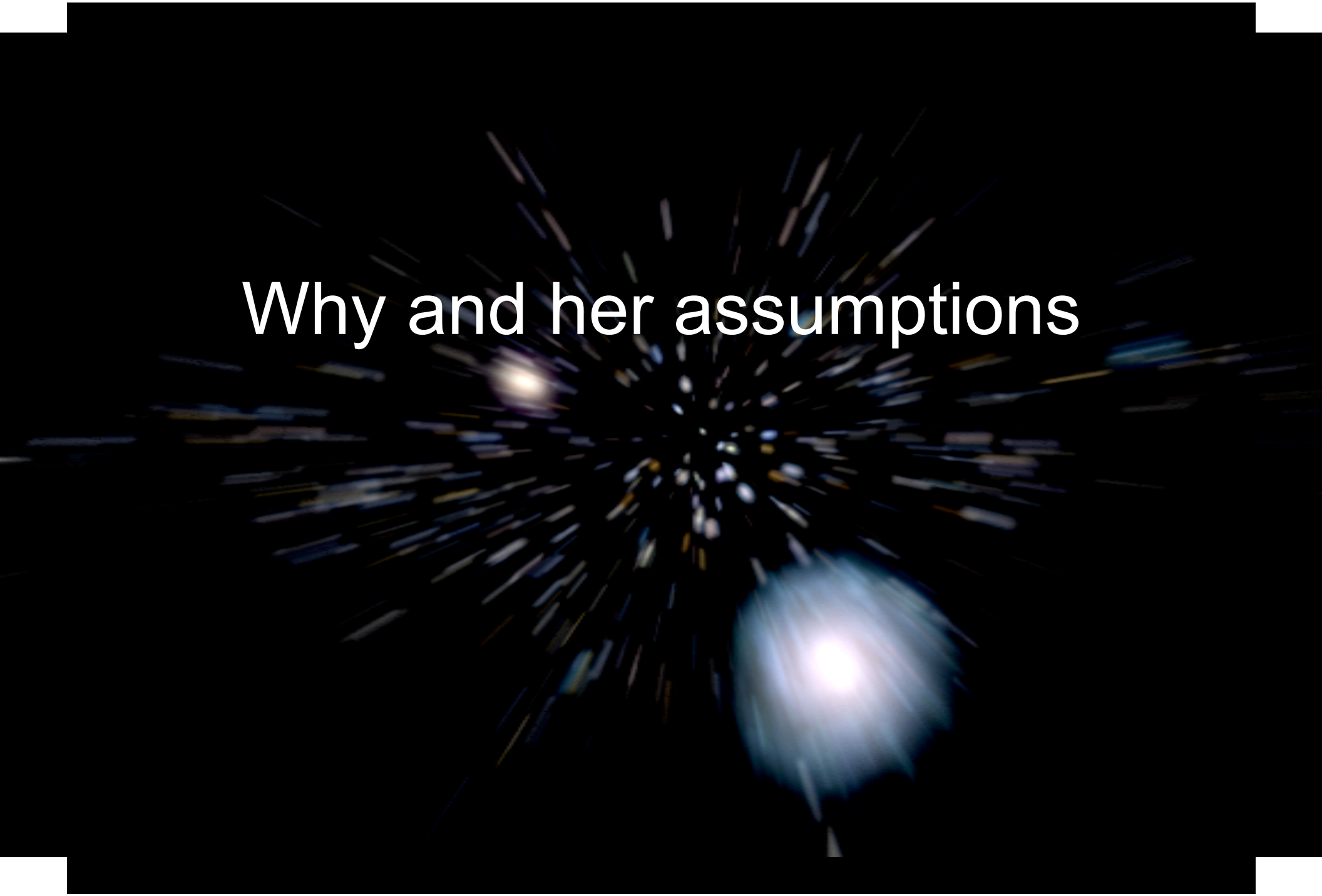

FICTION
For the Millions Who Cracked Up over
THE HITCHHIKER'S GUIDE TO THE GALAXY...
Dress Casual. Check Your Mind
at the Door, Your Table Is Ready at . . .
The Restaurant at the end of the Universe
Douglas Adams
POCKET · 44268-6 · $2.95


DISASTER AREA
DEAD END
THE END OF THE WORLD IS NIGH
MAGIC MUSHROOMS BEWARE!
42
Meaning of Life
DON'T PANIC!
Yes! You will Die
GO ROUND


HOTEL
AT THE END OF
UNIVERS
TEL:6680109, 6680011


What you learned at mother’s knee


SIZE
• Expansion = Scaling up
• Single "Cosmic Scale Factor"
R(t) Summarizes Expansion
• R = 1 today (convention)
Geometry
is
Destiny!
BIG BANG
TIME


Why and her assumptions

Mom's equations (FRW basics)

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{R^2}$$

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

$$d(\rho R^3) = -p\,d(R^3)$$

$$p = w\rho \;\Rightarrow\; \rho \propto R^{-3(1+w)}$$

$$\Omega_i \equiv \rho_i/(3H^2/8\pi G) \quad \text{and} \quad \Omega_0 = \sum_i \Omega_i$$

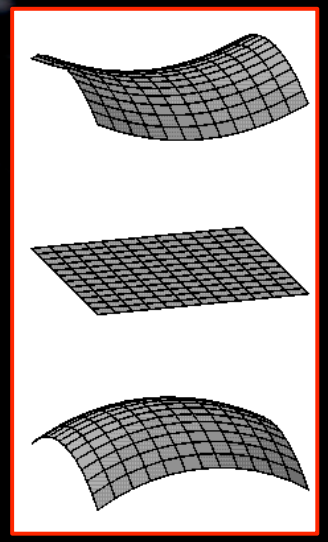
$$\Rightarrow k/R^2 = (\Omega_0 - 1)H_0^{-2}$$

Ω_0:

< 0

= 0

> 0



Space tells matter how to move
Matter tells space how to curve

$$
\begin{aligned}
d(\rho R^3) &= -p d(R^3) && \text{“First Law”} \\
\rho &\propto R^{-3(1+w)} && \text{for } p = w\rho
\end{aligned}
$$

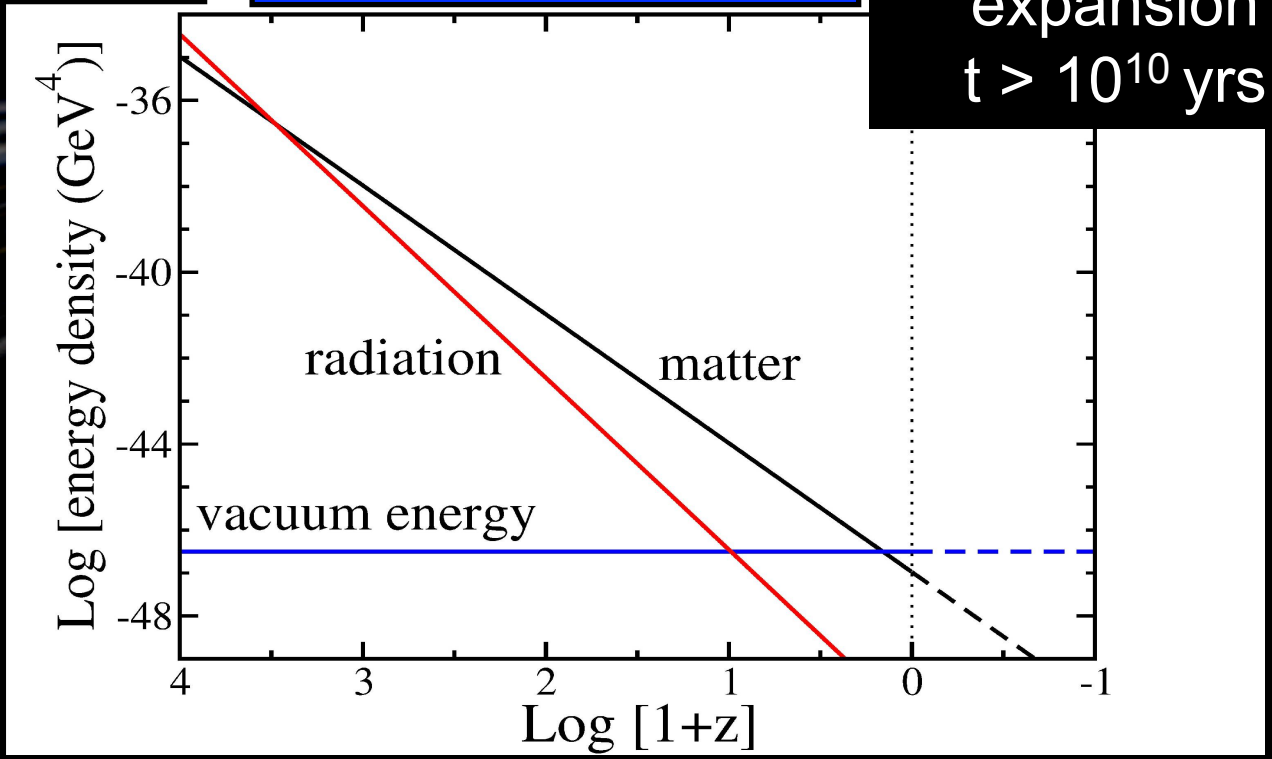
Matter ($w = 0$): $\rho \propto R^{-3}$ $R \propto t^{2/3}$
Radiation ($w = 1/3$): $\rho \propto R^{-4}$ $R \propto t^{1/2}$
Vacuum Energy ($w = -1$): $\rho \propto \text{const}$ $R \propto \exp(Ht)$

Three Epochs Dominated by Different Forms of Energy

1. Rad dominated
$R \sim t^{1/2}$ thermal bath
$R < 10^{-4}$, $t < 10^{4}$ yrs

2. Matter dominated
$R \sim t^{2/3}$ struc. forms
$t \sim 10^{4}$ yrs – 10^{10} yrs

3. Dark Energy
$R \sim e^{Ht}$
accelerated expansion
$t > 10^{10}$ yrs



Mom's Universe: matter only

Reformulate Friedmann 1 as particle in a one-d potential

$$R^2 \times H^2 \quad \Rightarrow \quad \dot{R}^2 = R^2 \frac{8\pi G\rho}{3} - k$$

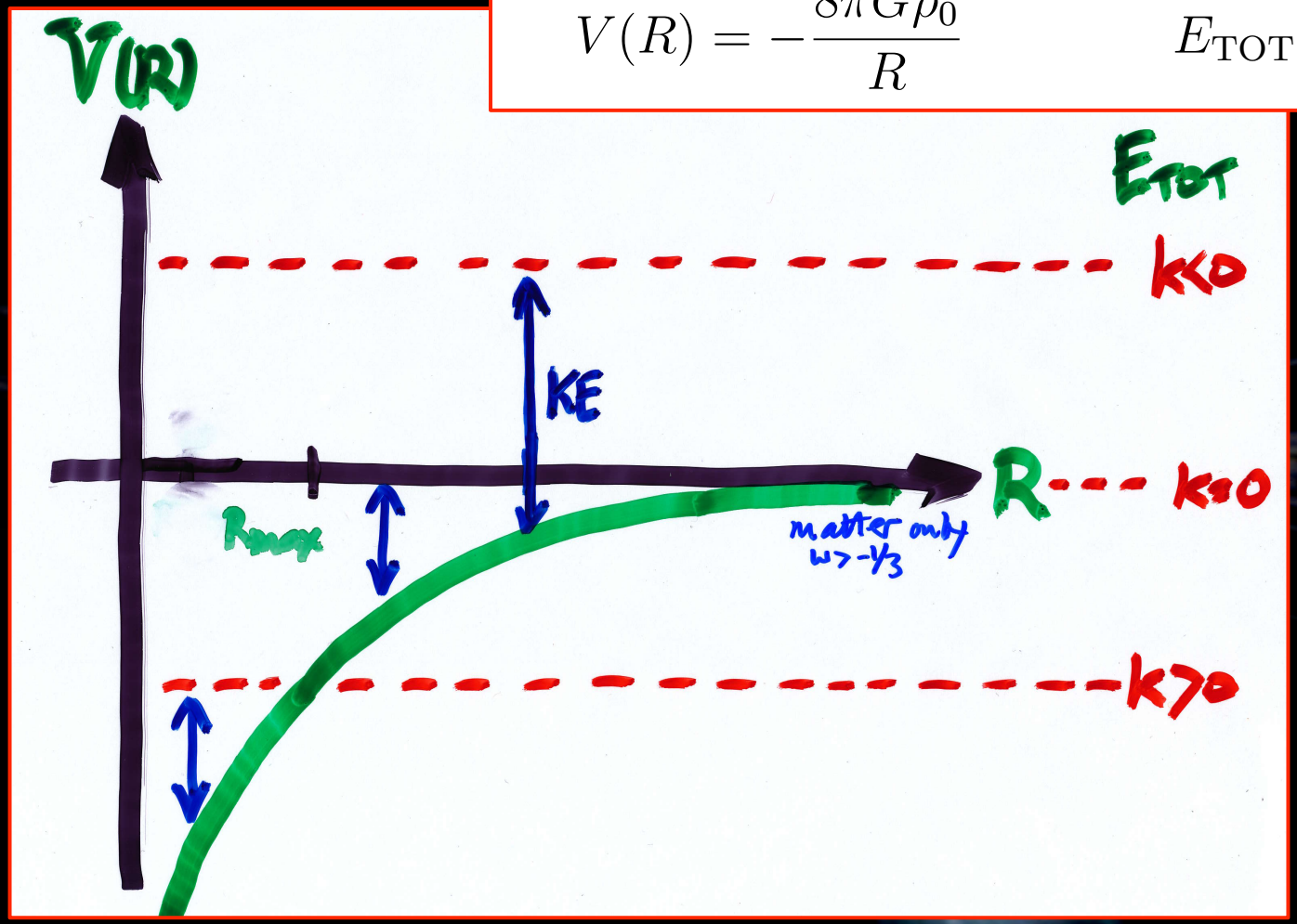
$$\begin{aligned} \dot{R}^2 - \frac{8\pi G\rho_0}{3R} &= -k \\ KE + V(R) &= E_{\rm TOT} \end{aligned}$$

Matter only

Particle in a one-d potential V(R):

$$\dot{R}^2 + V(R) = E_{\rm TOT}$$

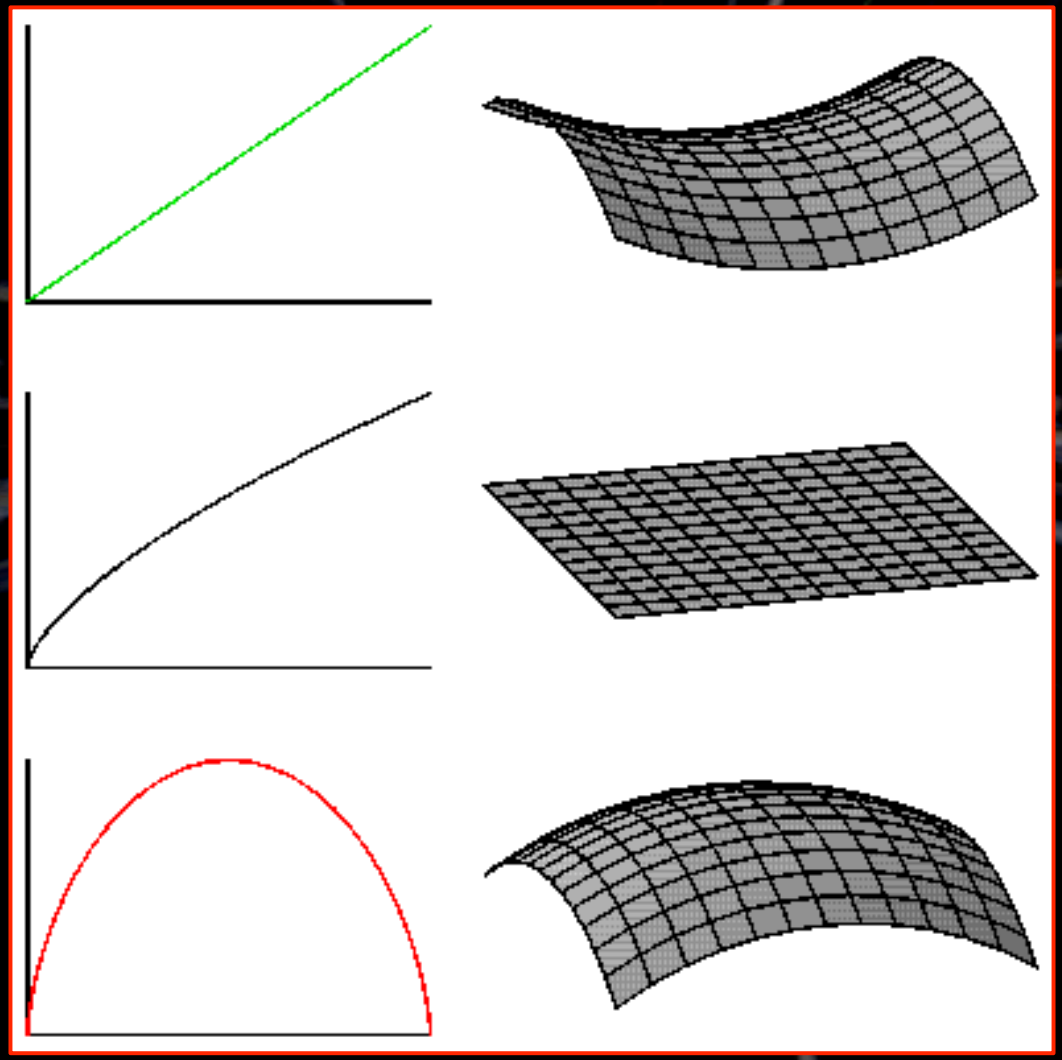
$$V(R) = -\frac{8\pi G\rho_0}{R} \qquad E_{\rm TOT} = -k$$

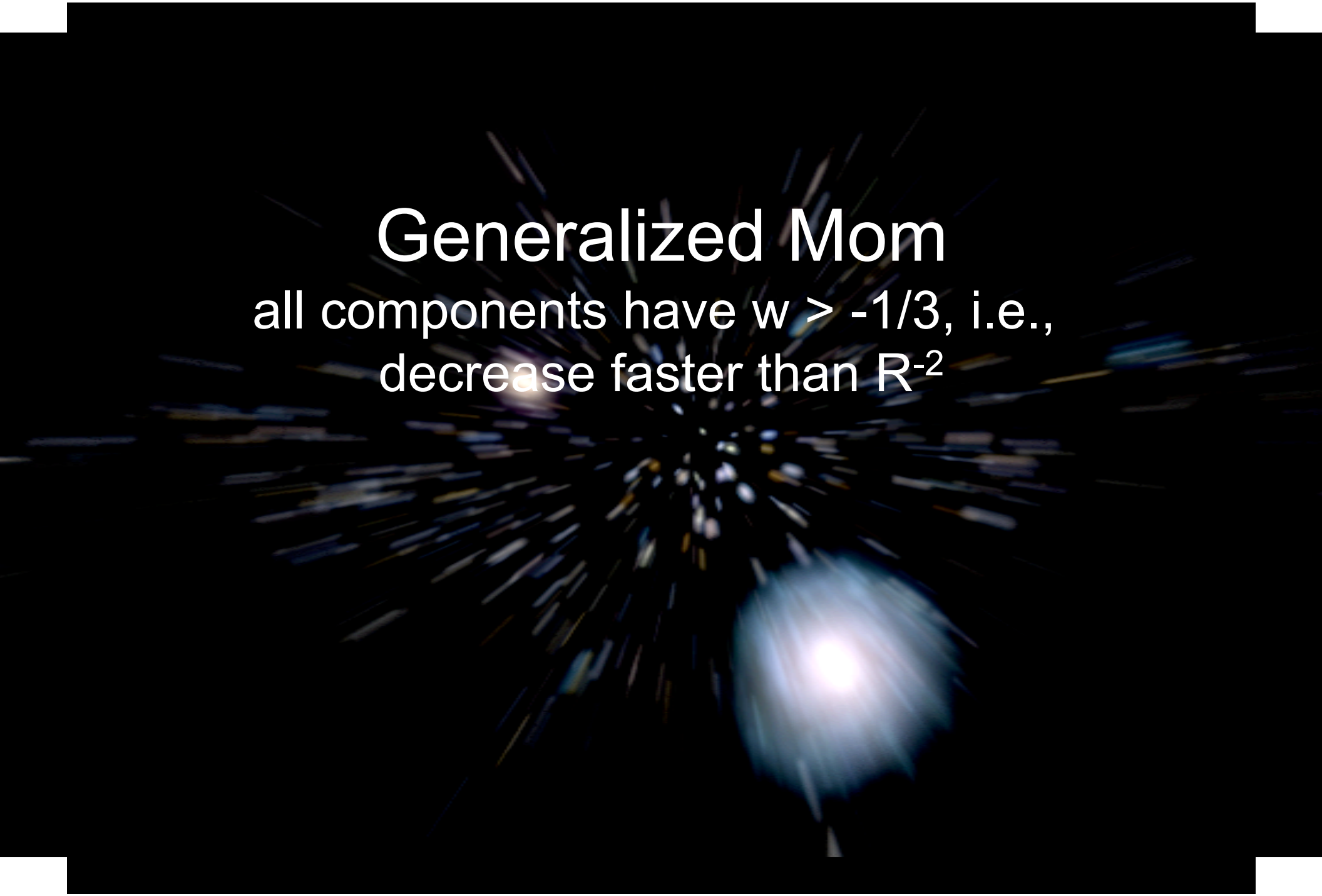


$k > 0 \rightarrow R_{max}$ & recollapse; $k = 0$ or < 0 expand forever

Geometry is Destiny

Just like Mom said!



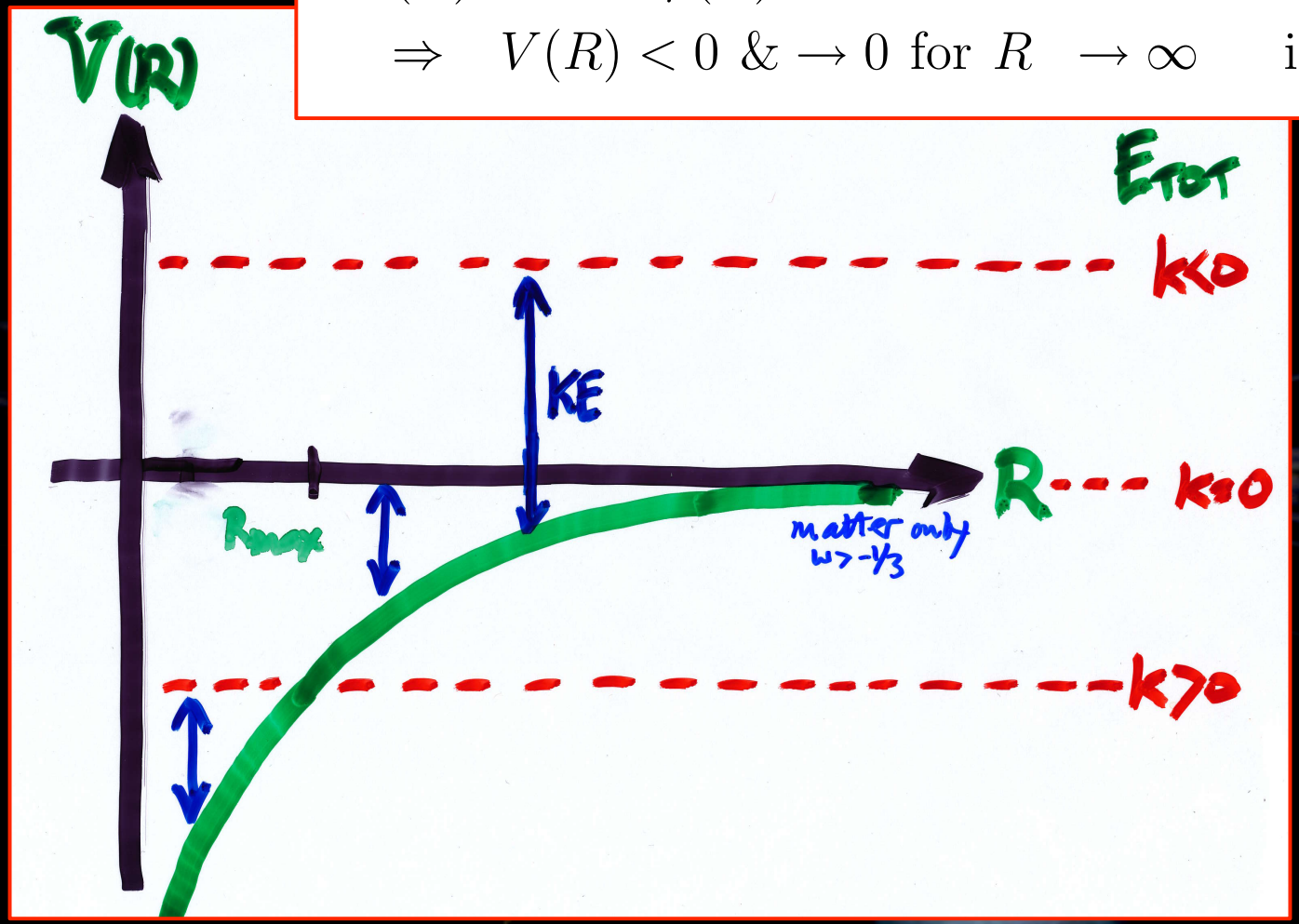

Generalized Mom
all components have w > -1/3, i.e.,
decrease faster than R^{-2}

"Ordinary Matter"

Particle in a one-d potential V(R):

$$V(R) \propto R^2 \quad \rho(R) \propto R^{-1-3w}$$

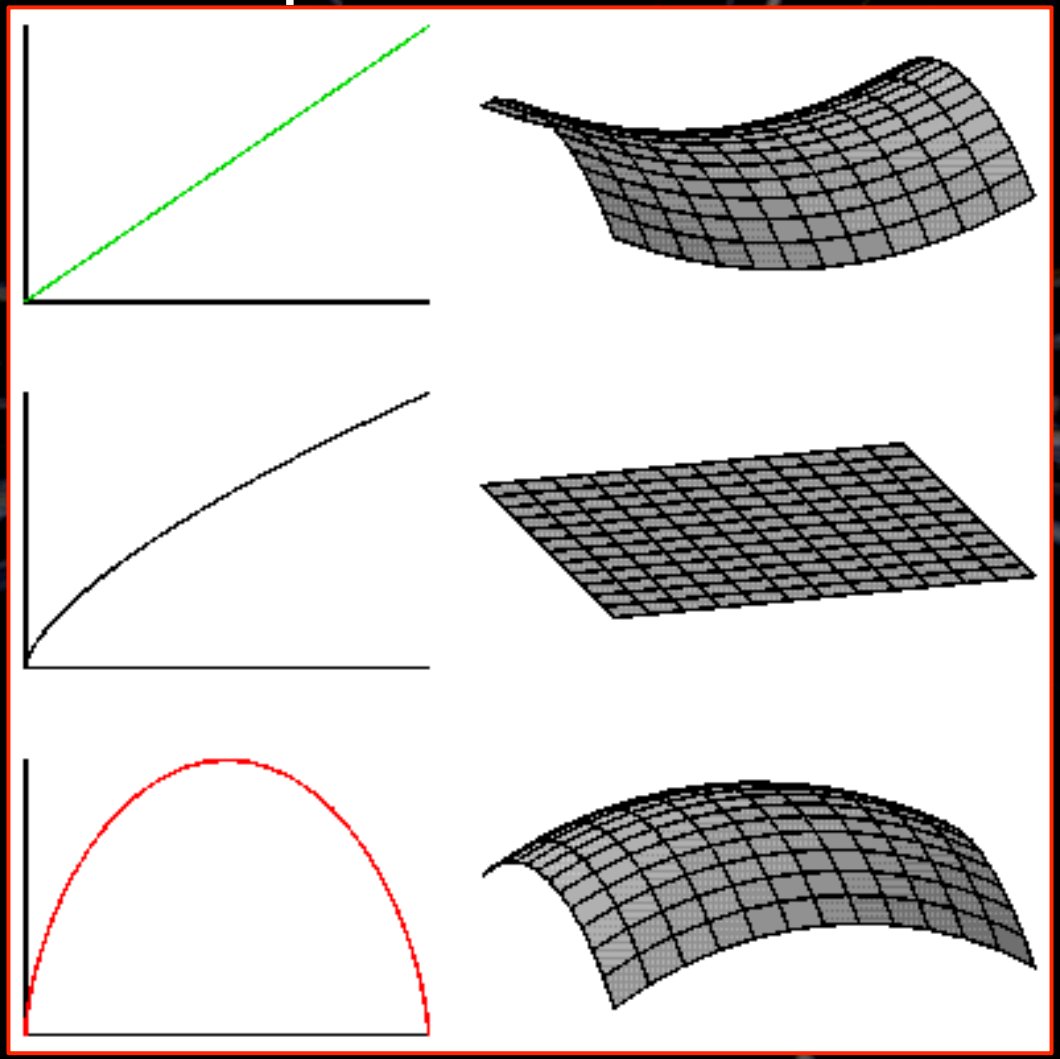
$$\Rightarrow \quad V(R) < 0 \;\&\; \to 0 \text{ for } R \to \infty \qquad \text{if } w > -1/3$$

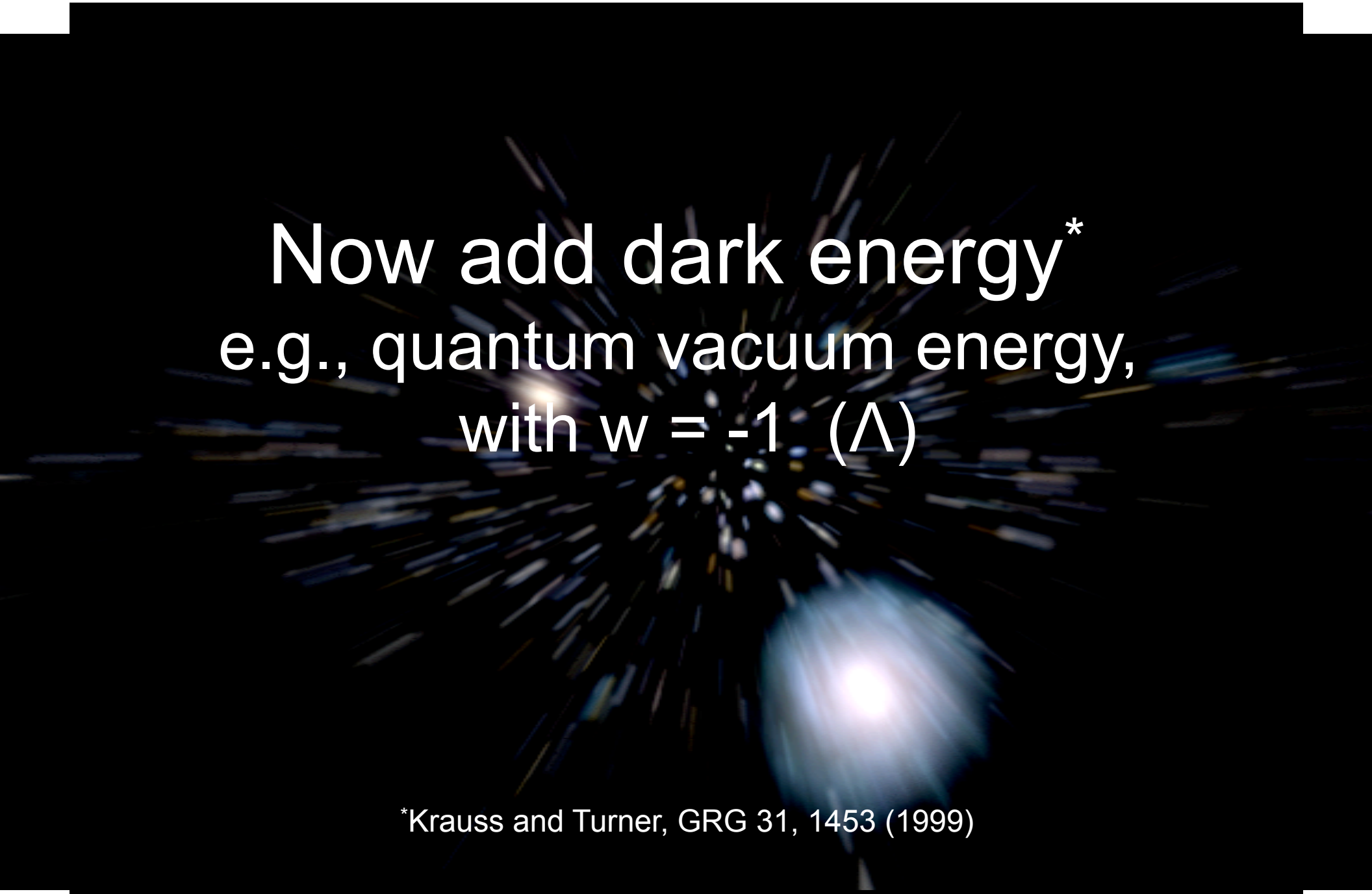


k > 0 → R_{max} & recollapse; k = 0 or < 0 expand forever

Geometry is Destiny!

(if all components have w > -1/3)





*Krauss and Turner, GRG 31, 1453 (1999)

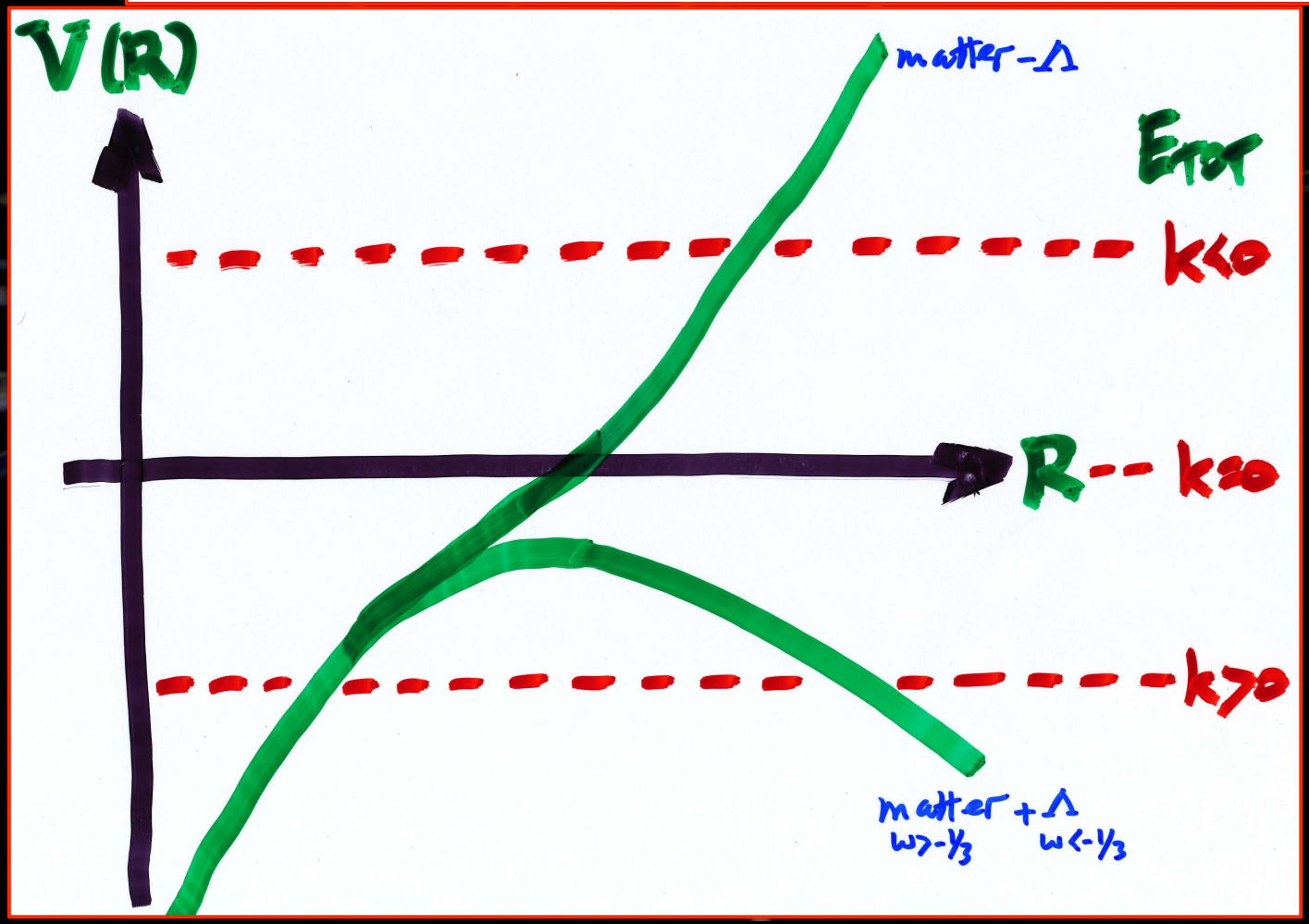
"Matter + DE"

Homework Problem

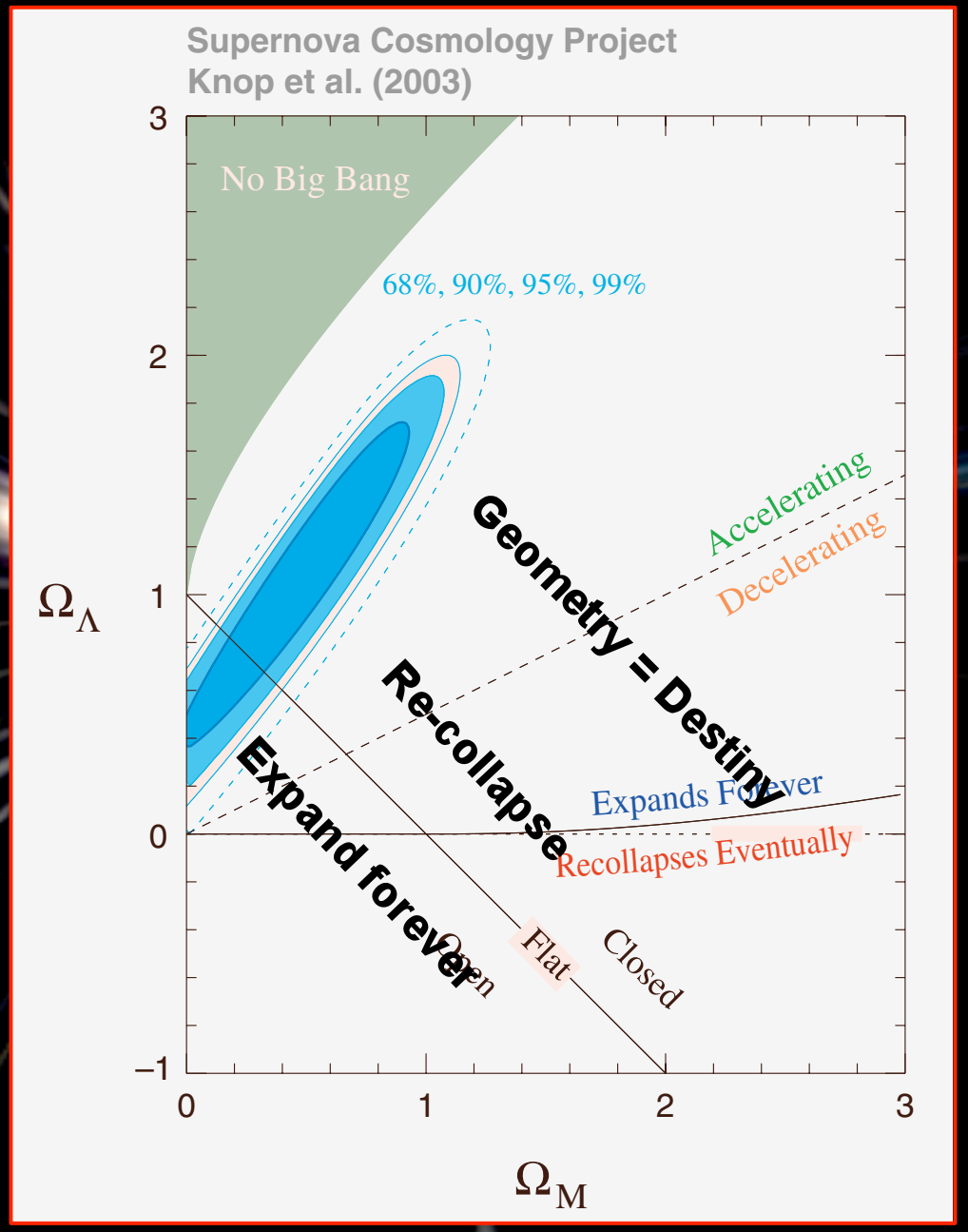
Particle in a one-d potential V(R):

$$\dot{R}^2 + V(R) = E_{\rm TOT}$$

$$V(R) = -\frac{8\pi G\rho_0}{R} - \frac{8\pi G\rho_{\rm VAC}}{3}R^2 \qquad E_{\rm TOT} = -k$$



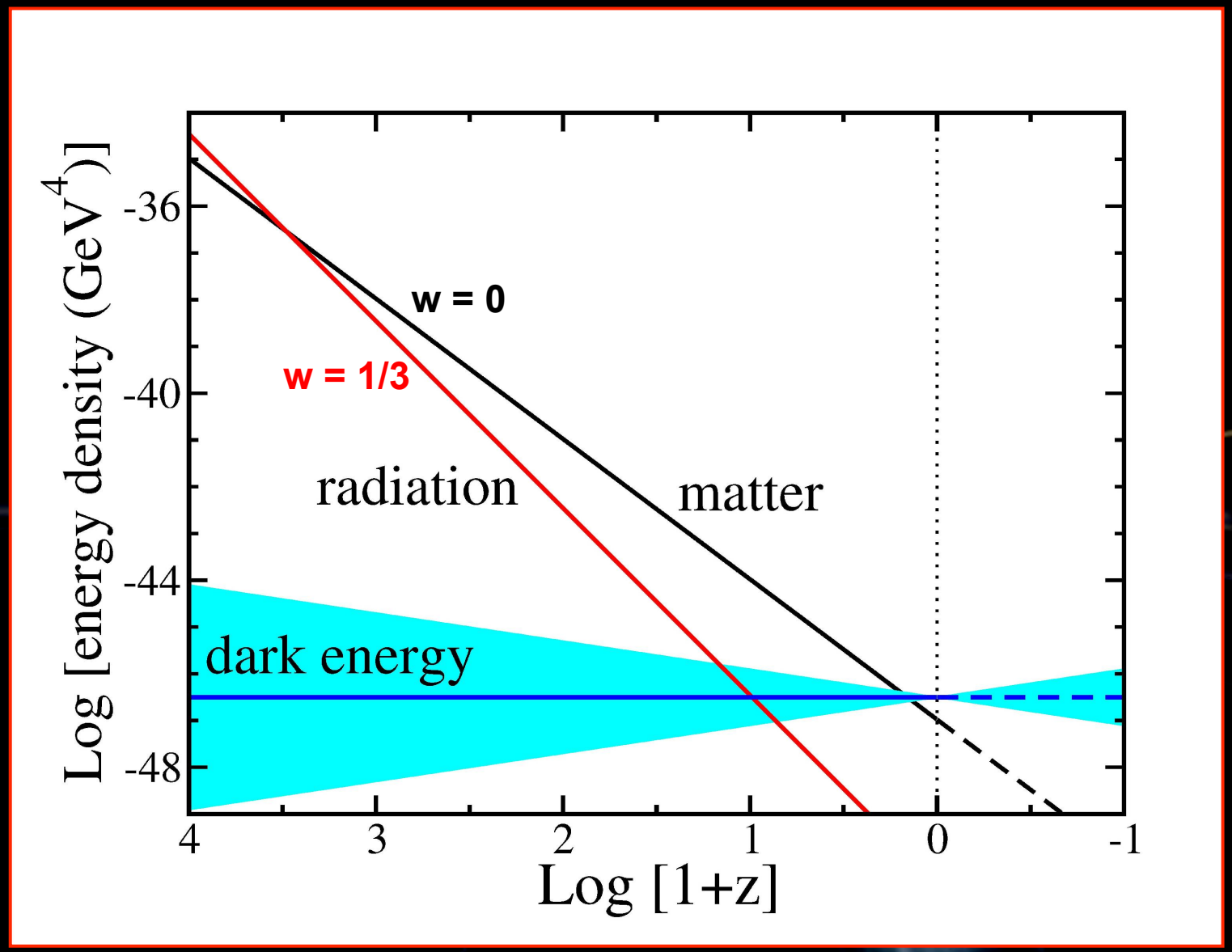
Answer to the HW problem



Duality and the Big Rip*

if w < -1, dark energy density increases with time leading to a future singularity and the disassembly of ALL structures in the Universe

*Caldwell et al, PRL 91, 071301 (2003)


Log [energy density (GeV^4)]
-36
-40
-44
-48
w = 0
w = 1/3
radiation
matter
dark energy
4
3
2
1
0
-1
Log [1+z]

w < -1
w = -1
w > -1

Re-formulate the problem: x = 1/R, t → -t, & w → w'

$$\text{Recall} \quad \rho_{\rm DE} \quad \propto \quad R^{-3(1+w)}$$

$$\text{if } w > -1 \quad \Rightarrow \quad R \propto t^{2/3(1+w)}$$

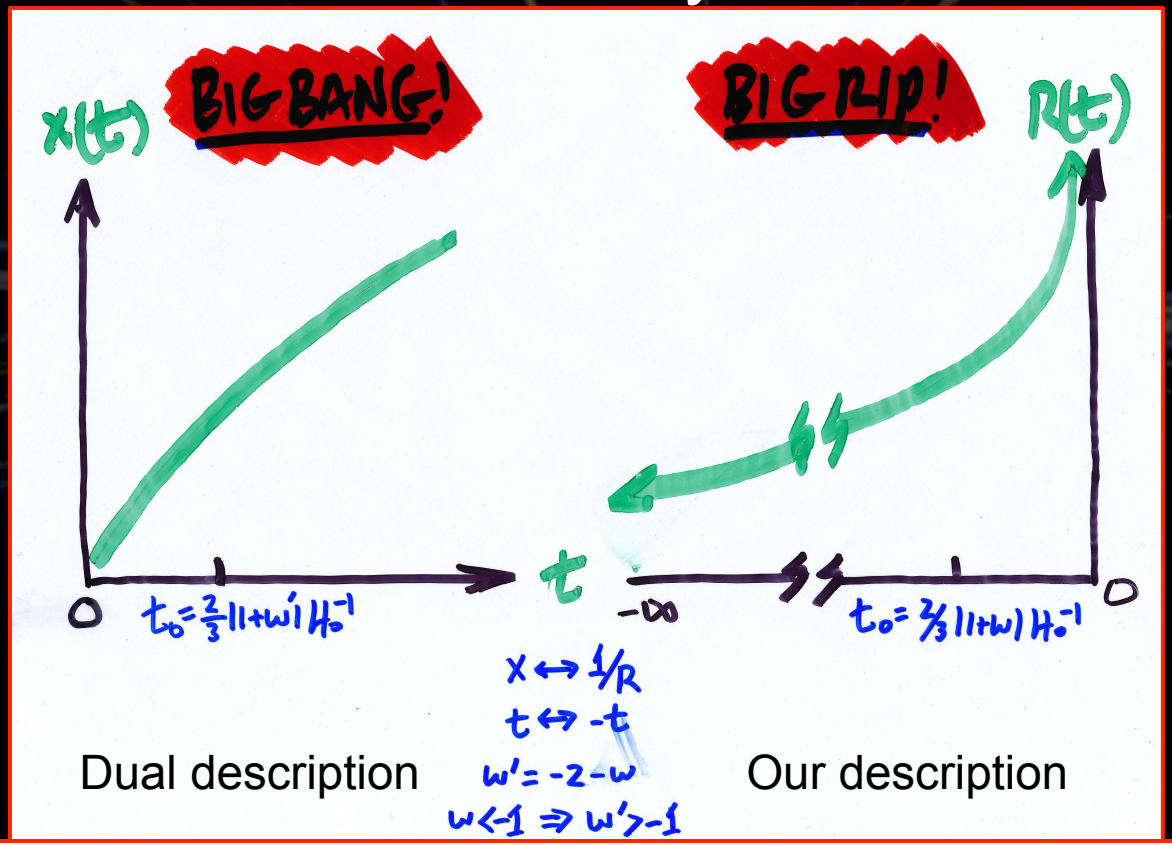
→ **Big bang, etc**

$$\text{if } w < -1 \quad \text{then} \quad \rho_{\rm DE} \propto R^n \quad \text{with} \quad n > 0 \quad \text{and ??}$$

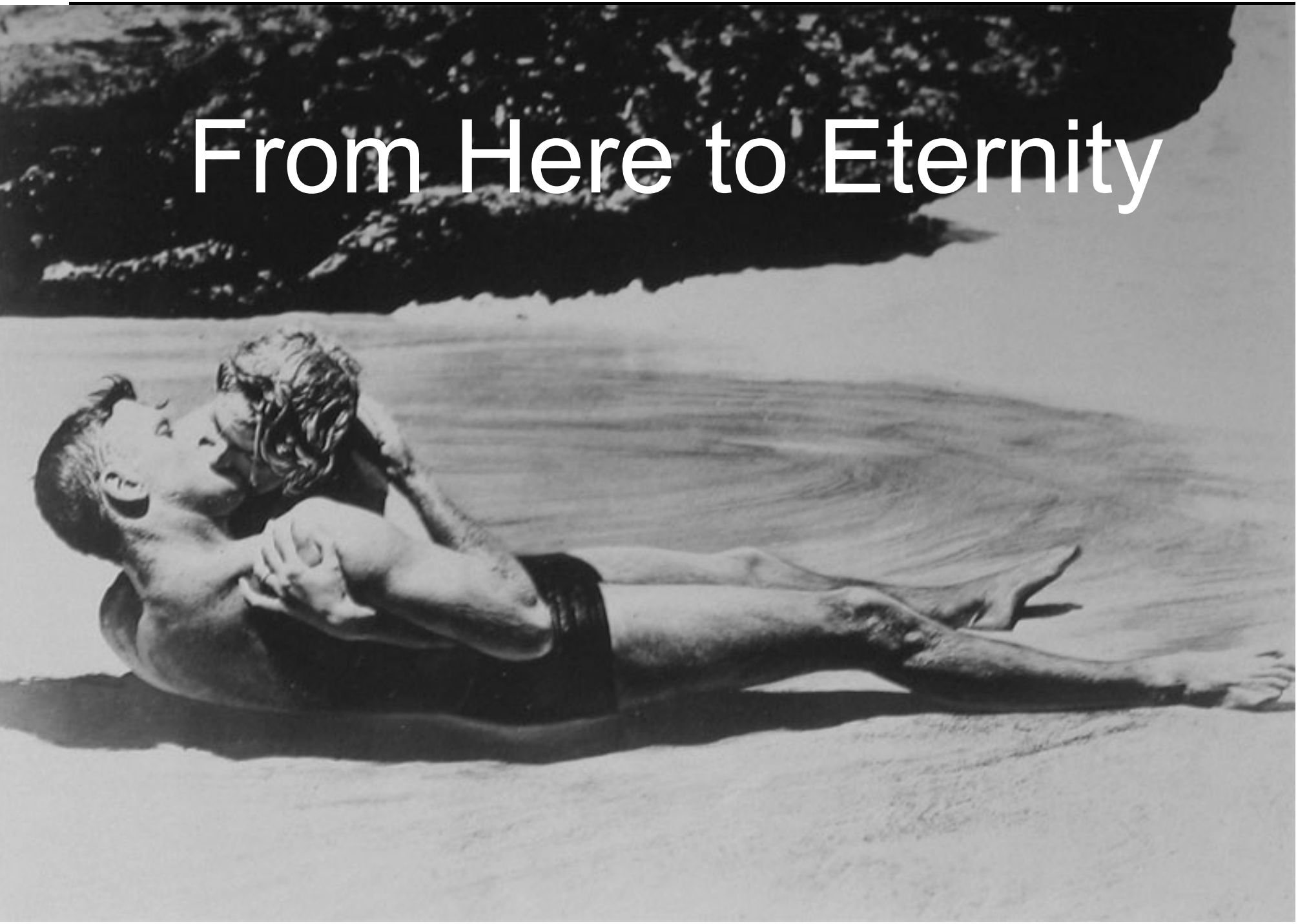
$$\textbf{Try dual} \quad x \equiv 1/R \qquad t \to -t \qquad H_x = H_R \qquad \text{with} \quad w' = -2 - w$$

$$H_x^2 = \frac{8\pi G}{3} x^{-3(1+w')} \qquad \text{for} \qquad w < -1 \text{ we have } \; w' > -1 \; \text{ and big bang solution}$$

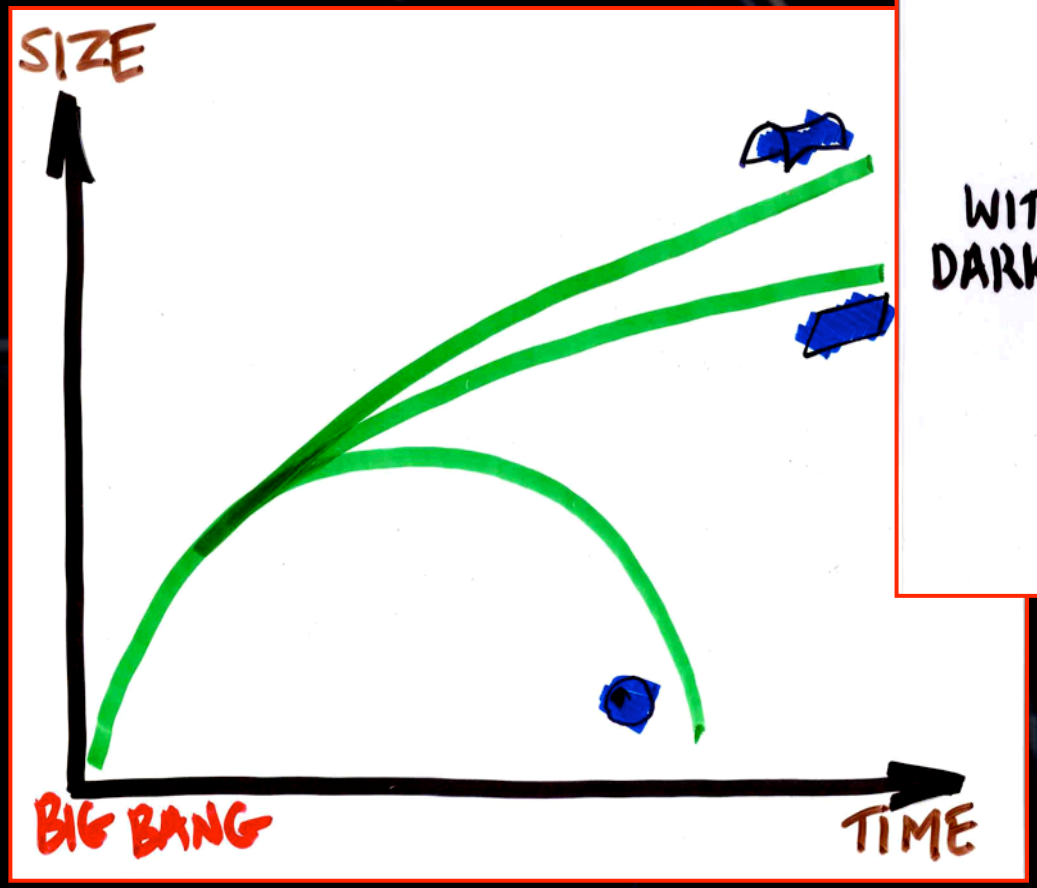
Dual picture: standard big bang (finite time back to bang, expansion forever) →
Our picture: infinite time back to R = 0 and finite time to infinite density & R = ∞

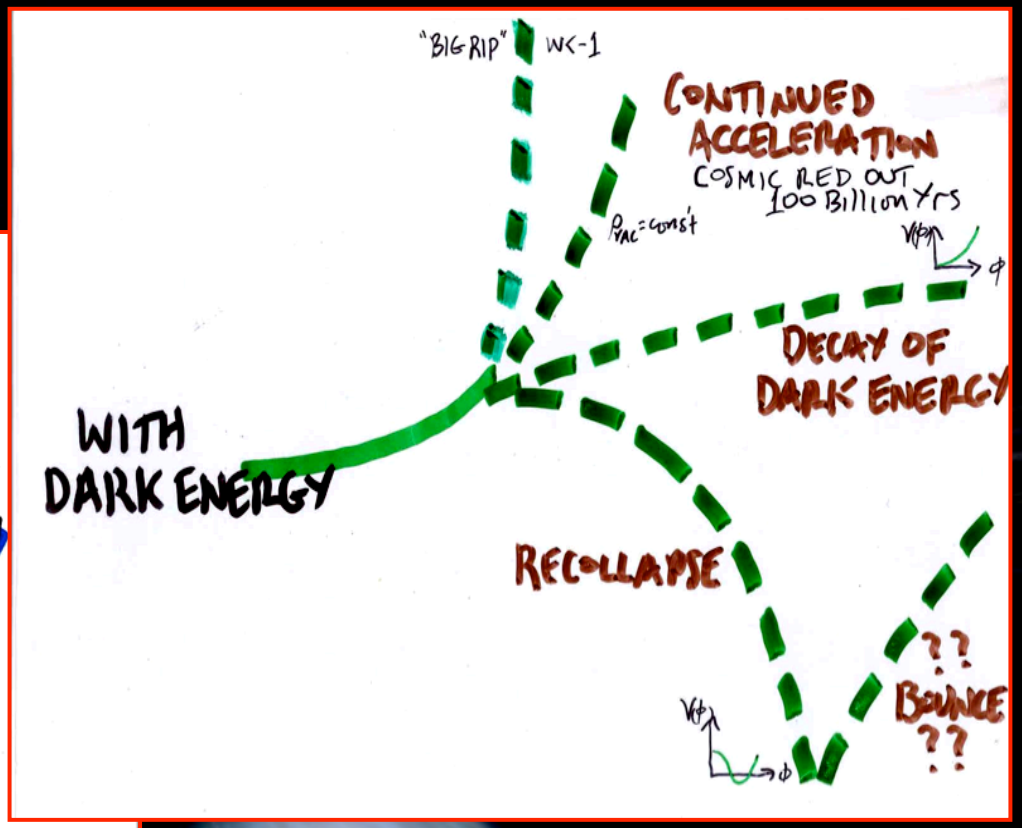


$$R(t) \quad \propto \quad (-t)^{2/3(1+w)} \qquad \text{today}: \quad t = -\frac{2}{3|1+w|} H_0^{-1}$$


From Here to Eternity

In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!

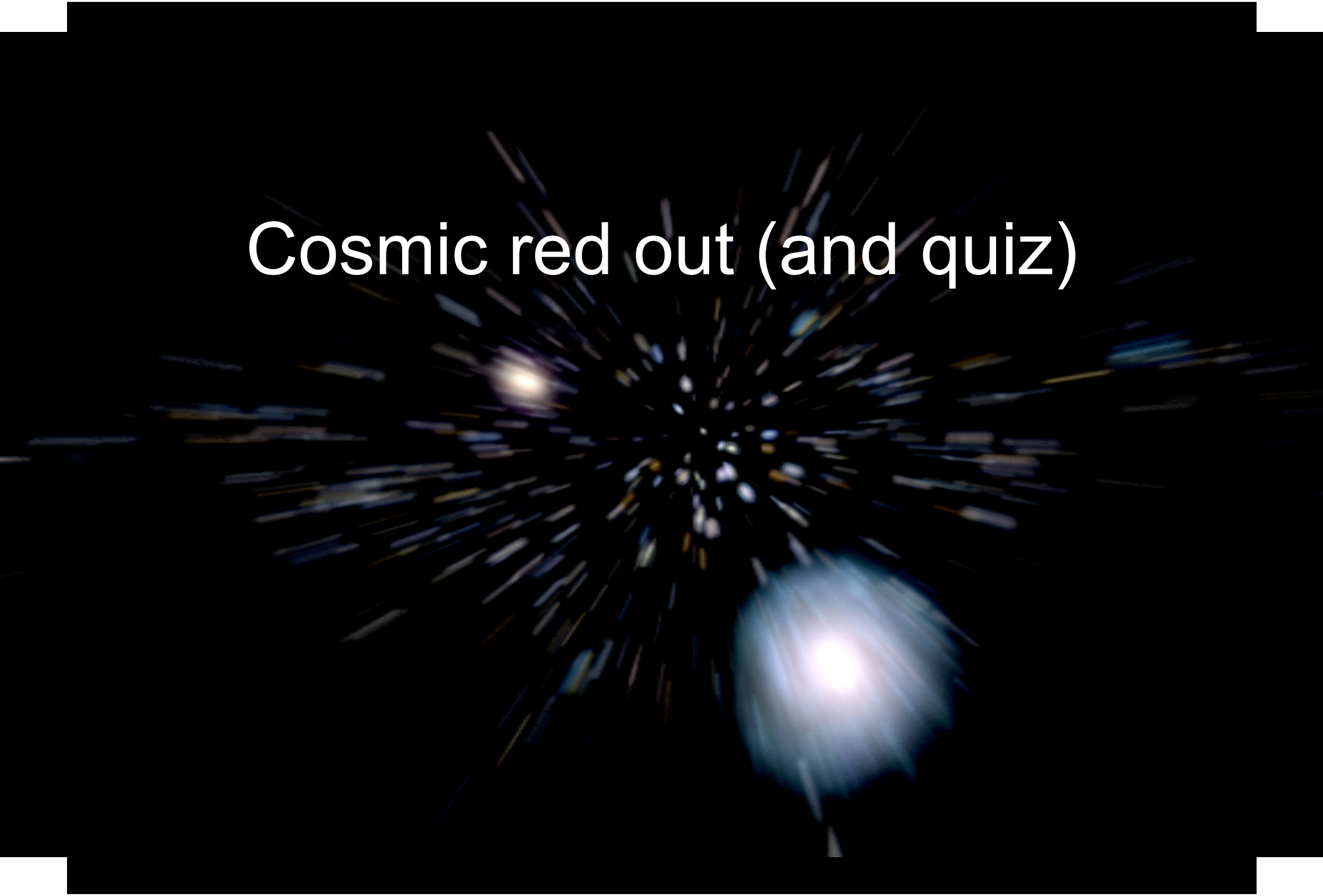




Cannot Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!

All destinies possible

- Expand forever
  - ΛCDM
  - Rolling scalar field + CDM
- Re-collapse
  - k > 0 + rolling scalar field
  - k = 0 + rolling scalar field –Λ
- Goldilocks (EdS)
  - k = 0 + rolling scalar field


Cosmic red out (and quiz)

Quiz

1. Which model Universe (dS or EdS) has more galaxies within the horizon (assuming same comoving galaxy density)? **dS or EdS (class says: 1 for dS, 80 for EdS)**
2. Which model Universe (dS or EdS) has more galaxies w/redshift less than O(10)? **dS or EdS (class says: 6 for dS & 12 for EdS)**

Answer

1. Which model Universe (dS or EdS) has more galaxies within the horizon (assuming same comoving galaxy density)? **de Sitter**

$$N_{\rm H} = \frac{4\pi}{3} n_{\rm GAL} r_{\rm H}^3$$

$$r_{\rm H} = \int dt'/R(t') = \int dz/H(z) = \int_0^{R(t)} dR'/R'^2 H(R')$$

$$r_{\rm H}({\rm dS}) = \infty \quad \Rightarrow \quad N_{\rm H}({\rm dS}) \to \infty$$

$$r_{\rm H}({\rm EdS}) = 2H_0^{-1}(t/t_0)^{1/3} \quad \Rightarrow \quad N_{\rm H}({\rm EdS}) = \frac{32\pi}{3} H_0^{-3}(t/t_0)$$

Answer

2. Which model Universe (dS or EdS) has more galaxies w/redshift less than O(10)?: **Einstein deSitter**

$$N_{z_*} = \frac{4\pi}{3} n_{\rm GAL} r_{z_*}^3$$

$$r_{z_*} = \int dt'/R(t') = \int dz/H(z) = \int_{R(t)/(1+z_*)}^{R(t)} dR'/R'^2 H(R')$$

$$r_{z_*}({\rm dS}) = H_0^{-1} z_*/R(t) \quad \text{and} \quad r_{z_*}({\rm EdS}) = 2H_0^{-1}(t/t_0)^{1/3}[1-1/(1+z_*)^{1/2}]$$

$$\Rightarrow \quad N_{z_*}({\rm dS}) = \frac{4\pi}{3} n_G z_*^3 R^{-3}(t) \quad \to 0 \quad \text{as} \quad R \to \infty$$

$$\Rightarrow N_{z_*}({\rm EdS}) = \frac{32\pi}{3} H_0^{-3}(t/t_0)[1-1/(1+z_*)^{1/2}]^3 \quad \propto \quad t$$

Footnote to Q1:

If one truncates the horizon integral at redshift of 1000 (CMB), because galaxies couldn't have formed before, then r_H = $1000/H_0$ and N_H(dS) → 0 as t → infinity and N_H(EdS) is larger.

$$N_{z_*} = \frac{4\pi}{3} n_{\rm GAL} r_{z_*}^3$$

$$r_{z_*} = \int dt'/R(t') = \int dz/H(z) = \int_{R(t)/(1+z_*)}^{R(t)} dR'/R'^2 H(R')$$

$$r_{z_*}({\rm dS}) = H_0^{-1} z_*/R(t) \quad \text{and} \quad r_{z_*}({\rm EdS}) = 2H_0^{-1}(t/t_0)^{1/3}[1-1/(1+z_*)^{1/2}]$$

$$\Rightarrow \quad N_{z_*}({\rm dS}) = \frac{4\pi}{3} n_G z_*^3 R^{-3}(t) \quad \to 0 \quad \text{as} \quad R \to \infty$$

$$\Rightarrow N_{z_*}({\rm EdS}) = \frac{32\pi}{3} H_0^{-3}(t/t_0)[1-1/(1+z_*)^{1/2}]^3 \quad \propto \quad t$$


The end of cosmology

Suppose dark energy is quantum vacuum energy

- In ~200 Billion years (15 e-folds):
  - $N_{GAL} \sim 10^{-20} N_{GAL}$ (today) << 1
  - $T_{CMB} \sim 10^{-7}$ 3K
- No expansion, no CMB → one galaxy (one cluster) + static Universe and no evidence of the big bang (Helium abundance?) – "Cosmic Amnesia"*

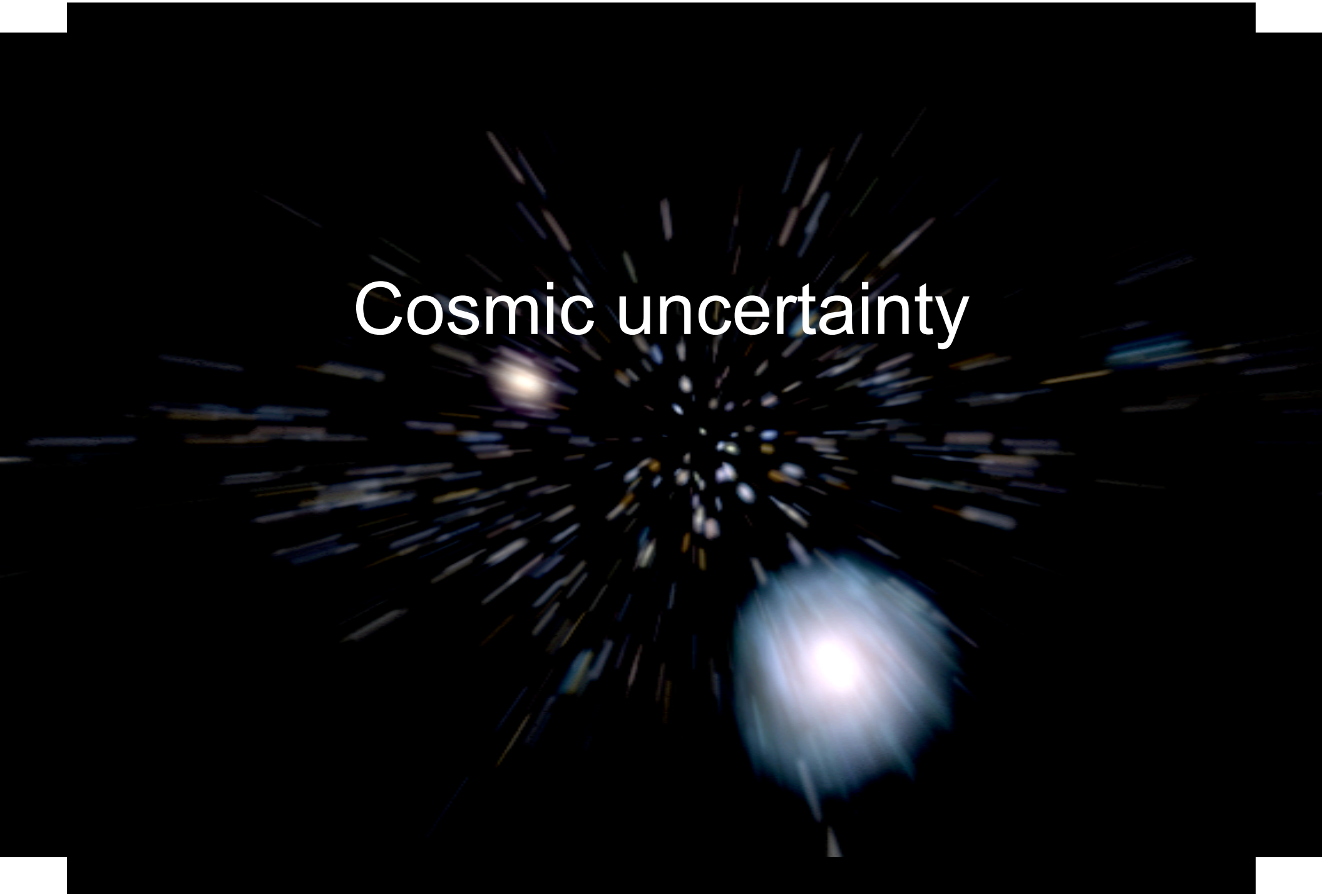
*Krauss and Scherrer, GRG 39, 1545 (2007)

Fall of cosmology!

Suppose dark energy is quantum vacuum energy

- In ~200 Billion years (15 e-folds):
  - $N_{GAL} \sim 10^{-20} N_{GAL}$ (today) << 1
  - $T_{CMB} \sim 10^{-7}$ 3K
- No expansion, no CMB → one galaxy (one cluster) + static Universe and no evidence of the big bang (Helium abundance?) – "Cosmic Amnesia"*

*Krauss and Scherrer, GRG 39, 1545 (2007)


Cosmic uncertainty

How well can we determine our cosmic destiny?* Suppose:

- Planck measures $\Omega_0 = 1.1$, DE = rolling scalar field (w/ undetected $\Omega_{VAC} = 0.001$)
  - Conclude that Universe re-collapses, but actually due to an undetectable QVE it will expand forever!
- Planck measures $\Omega_0 = 1.00$, DE = rolling scalar field (w/undetected $\Omega_{VAC} = -0.001$)
  - Conclude that Universe expands forever, but actually due to an undetectable small QVE it will re-collapse!

*Krauss and Turner, GRG 31, 1453 (1999)

Destiny question is much richer than your Mom expected!

The key to getting at our destiny is understanding dark energy/cosmic acceleration

No guarantees (as noted) – but, this appears to be the most promising path forward

What could we learn?

- Ω_0 to 1%, discovery that DE = rolling scalar field → end of accelerated expansion
- New theoretical understanding QVE (and proof that QVE = 0)
- Surprises: crack in GR, …

DARK ENERGY

MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY

Lessons from this story

- Humility in face of the vastness of Universe, which is often beyond the reach of our ideas and instruments is a good idea
- It is remarkable how far we have come with such simple ideas (isotropy, homogeneity, dark matter, inflation, …), cf. galaxy formation and evolution, but don't be taken in. ("For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation." – T. Gold)
- Be bold but be flexible and humble