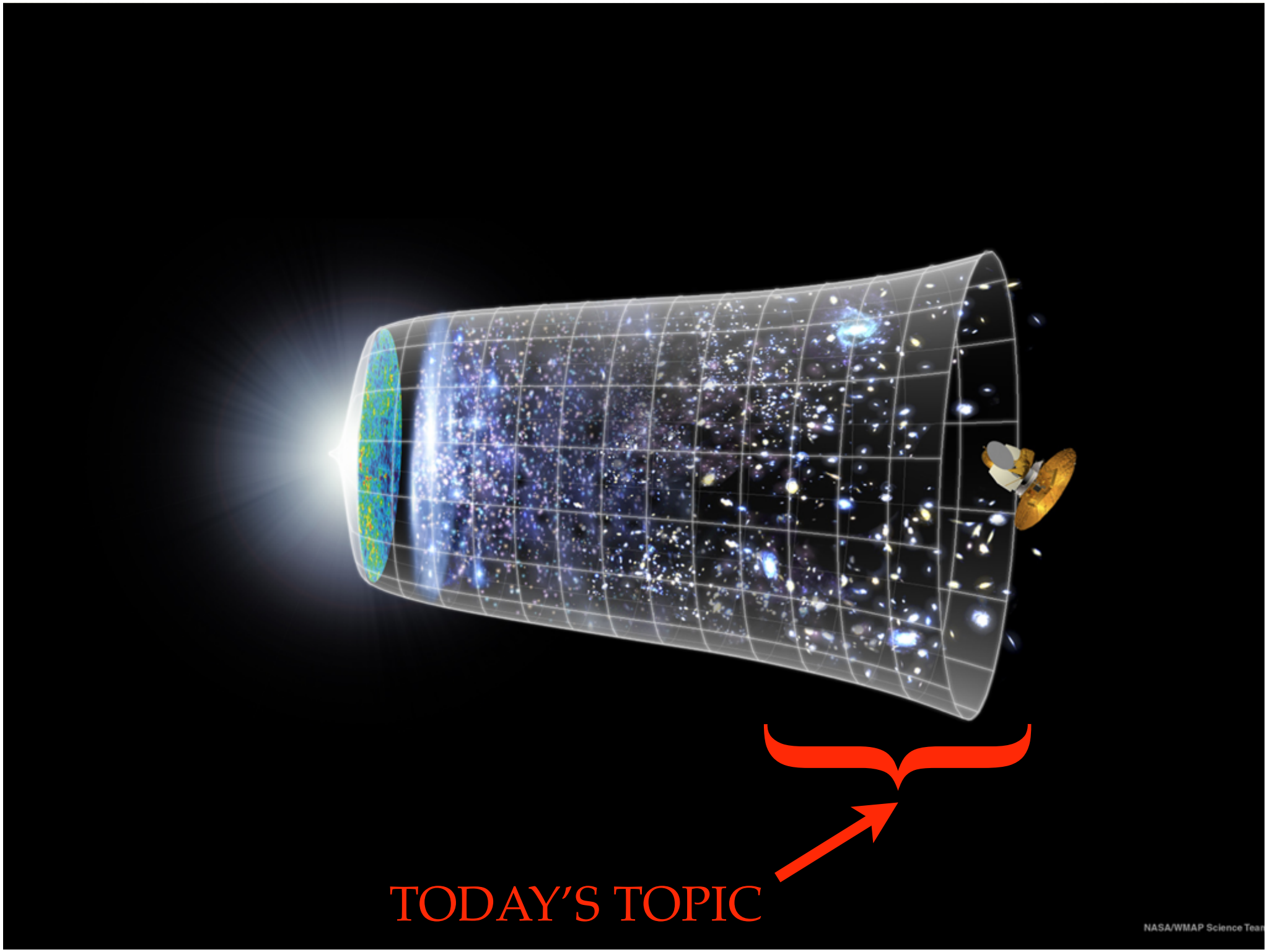
# The Dark Energy Crisis

Mark Wyman

74th Compton Lecture Series


TODAY'S TOPIC
NASA/WMAP Science Team

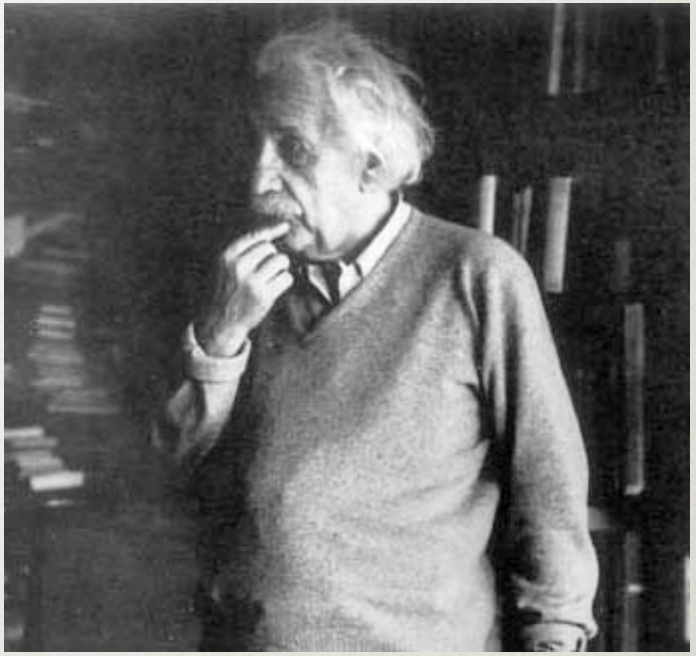
# 2011 Nobel Prize!


Saul Perlmutter  Brian Schmidt  Adam Riess

*...for the discovery of the accelerating expansion of the Universe through observations of distant supernovae*

# What is Dark Energy?

makes gravity
push *out,* instead
of pulling together



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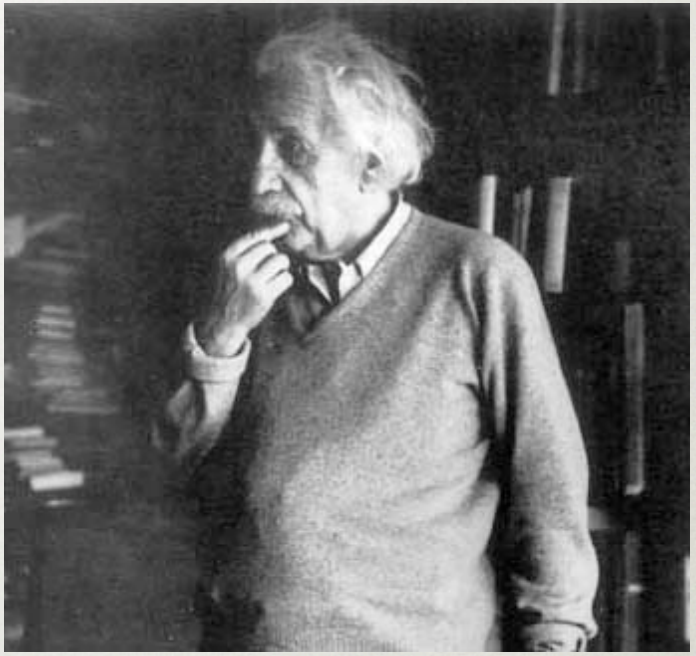
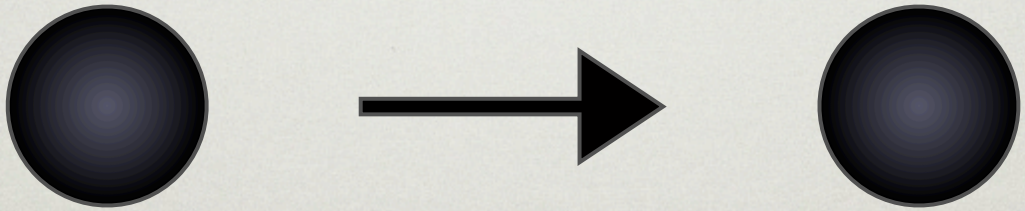
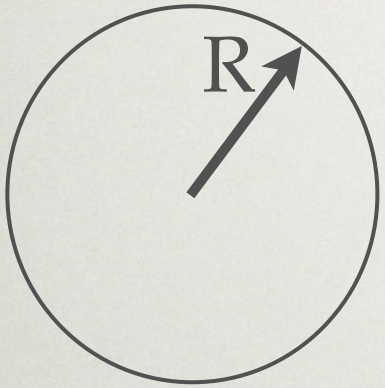
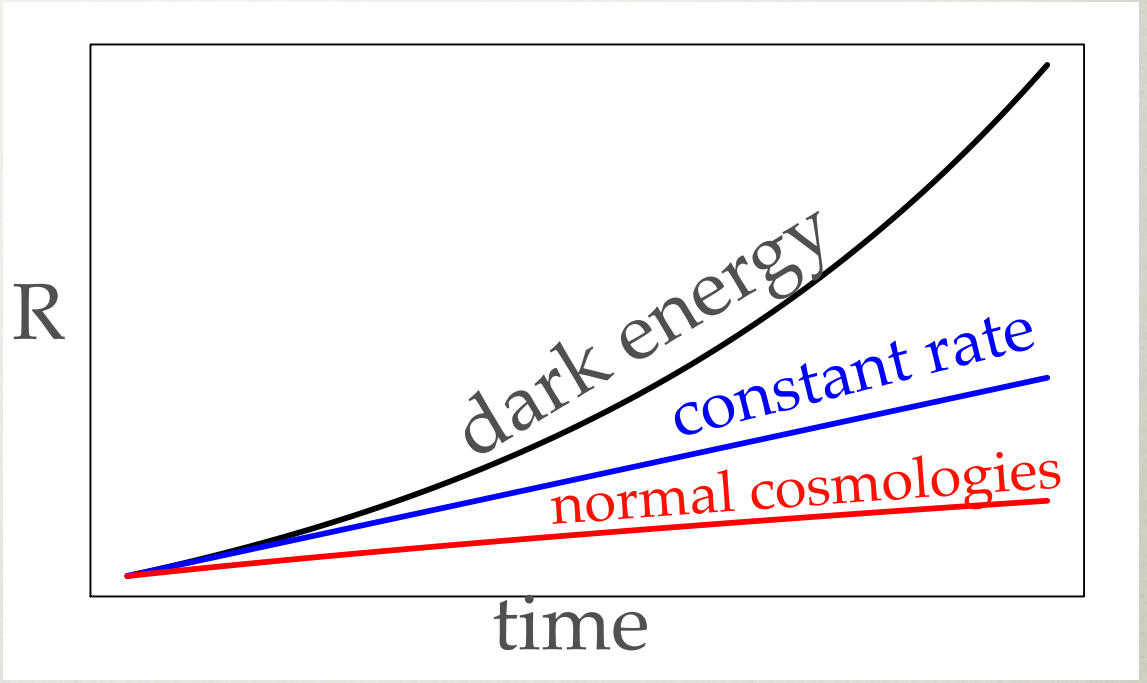




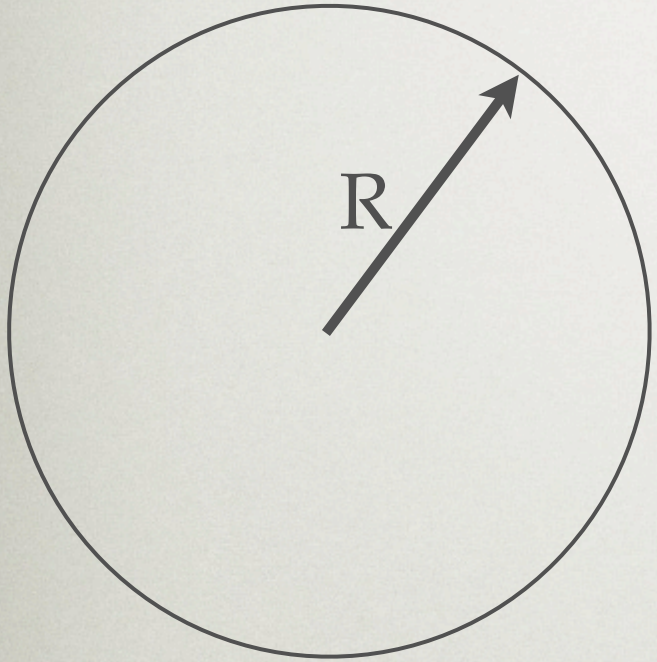
can allow "steady state" universe = Einstein's greatest blunder

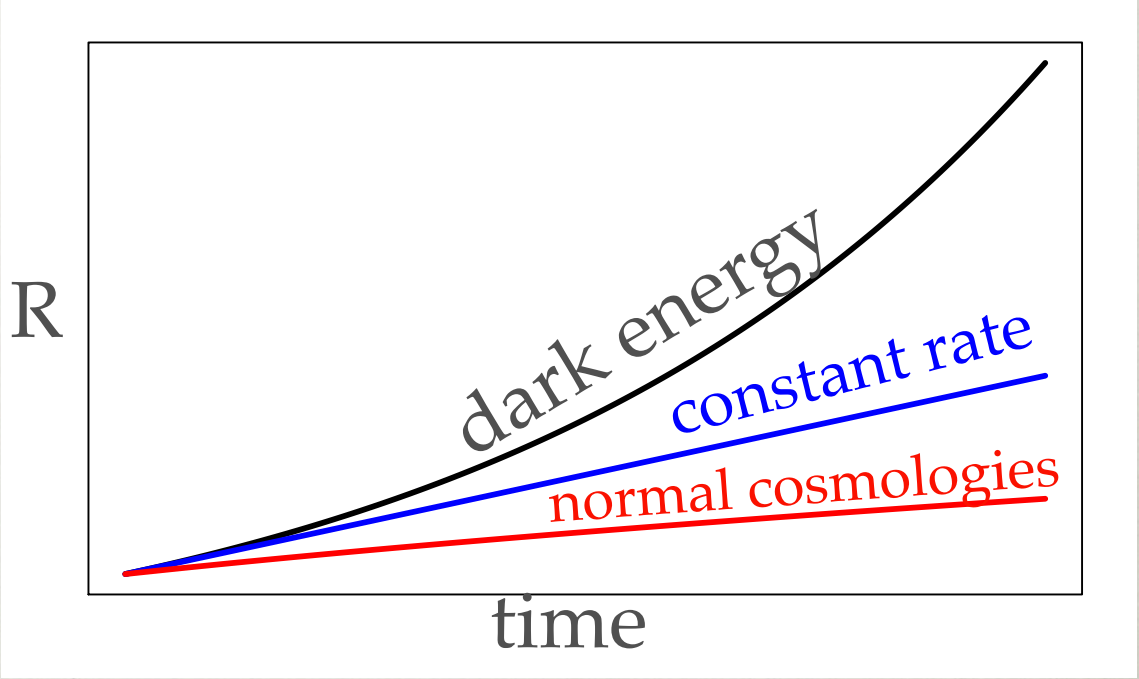
# What is Dark Energy?



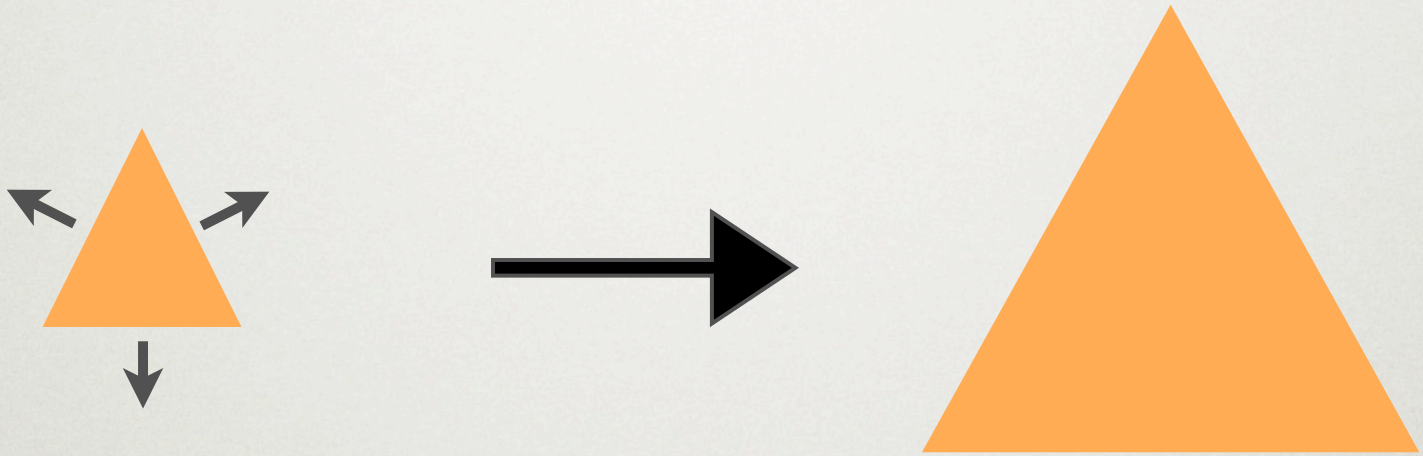



# What is Dark Energy?



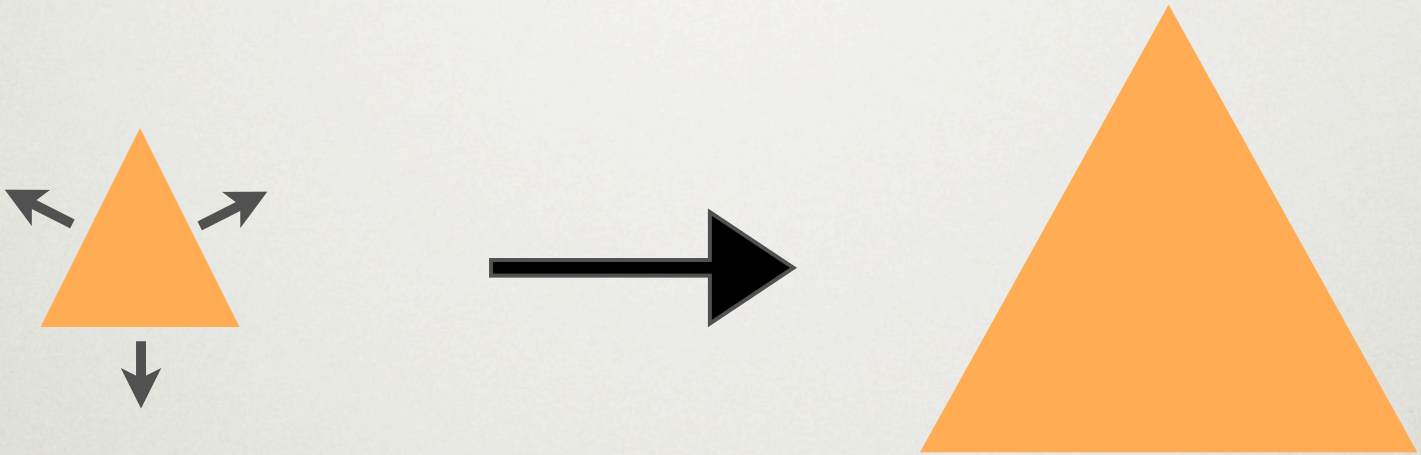



# Expansion of Space



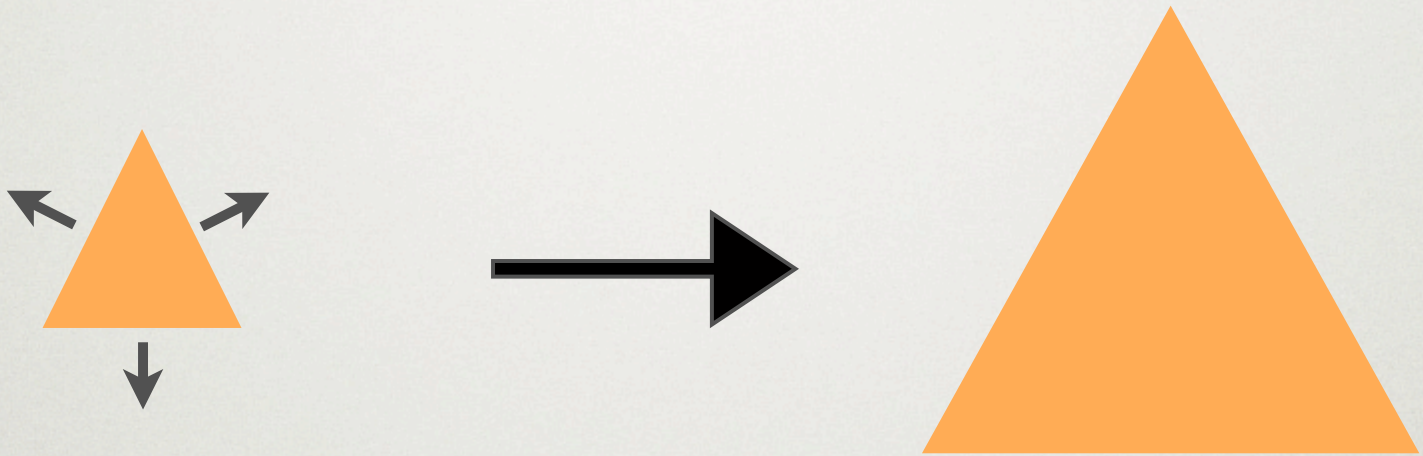
imagine: double each dimension

# Matter density dilutes more slowly



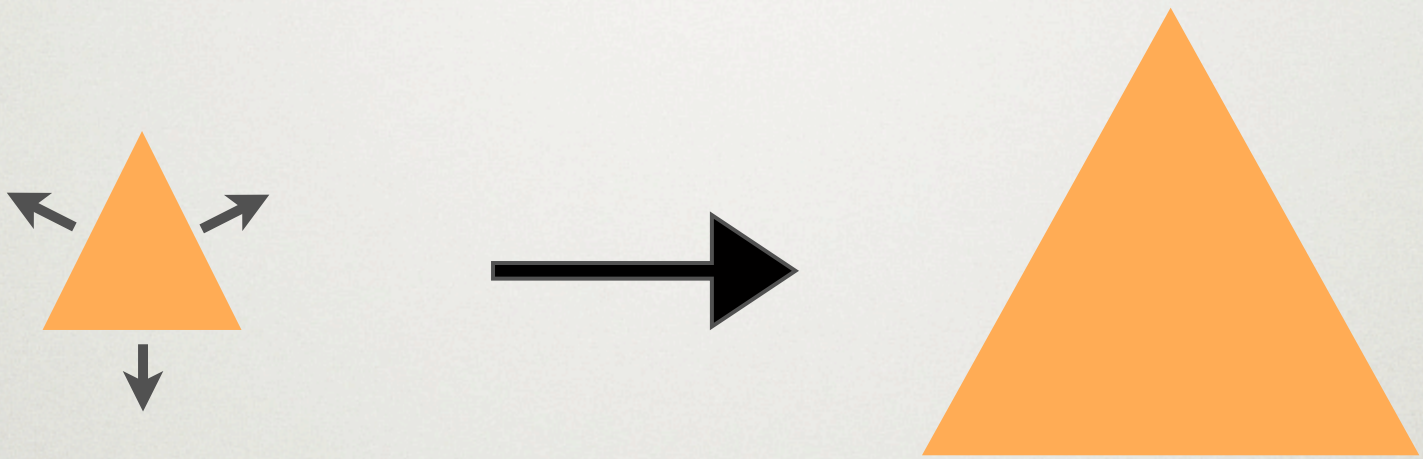
$$\rho \propto \frac{1}{L^3} \times 1 = \frac{1}{L^3}$$

# Radiation energy density dilutes quickly

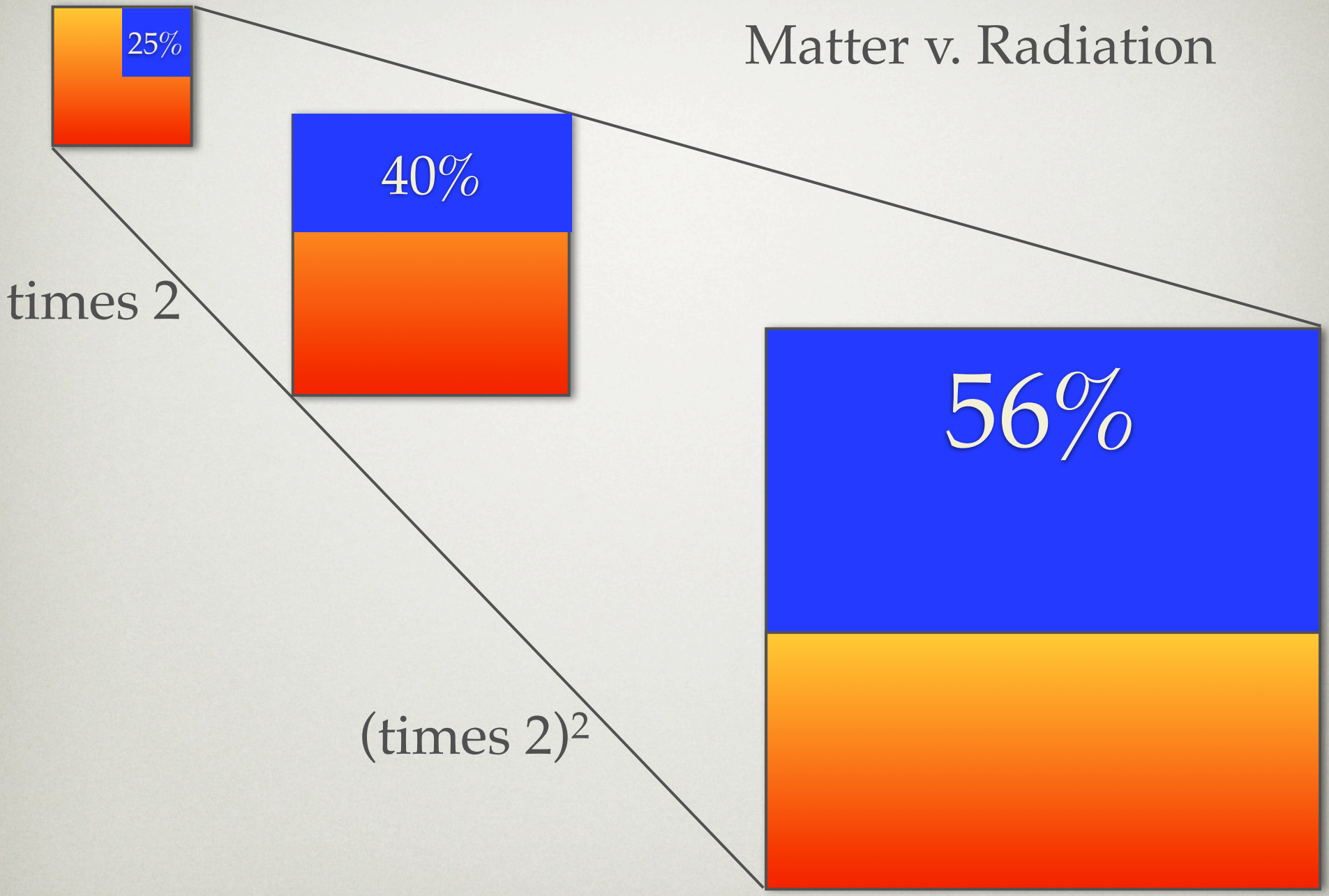


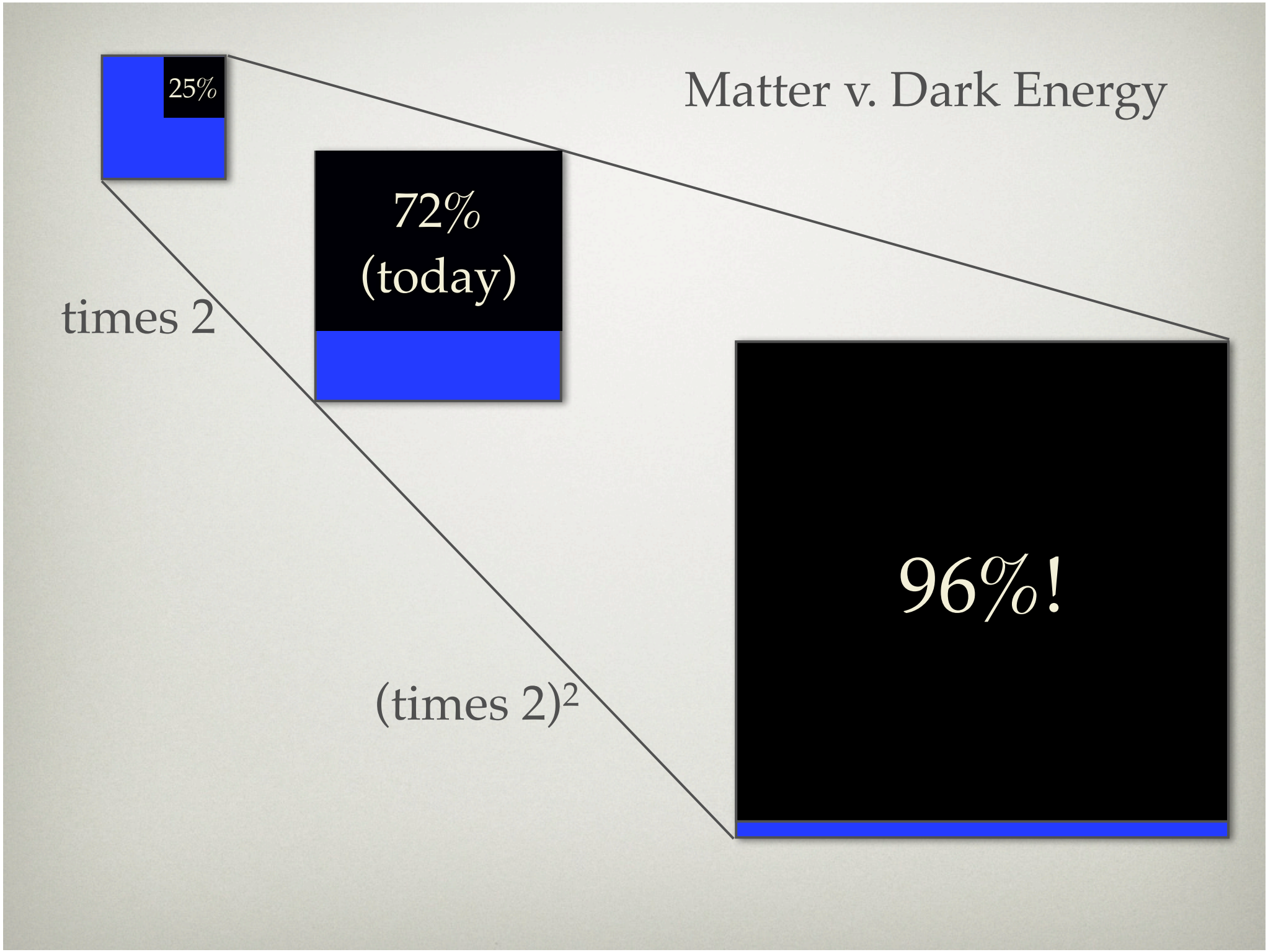
$$\rho \propto \frac{1}{L^3} \times \frac{1}{L} = \frac{1}{L^4}$$

# Dark energy density stays (nearly) CONSTANT!



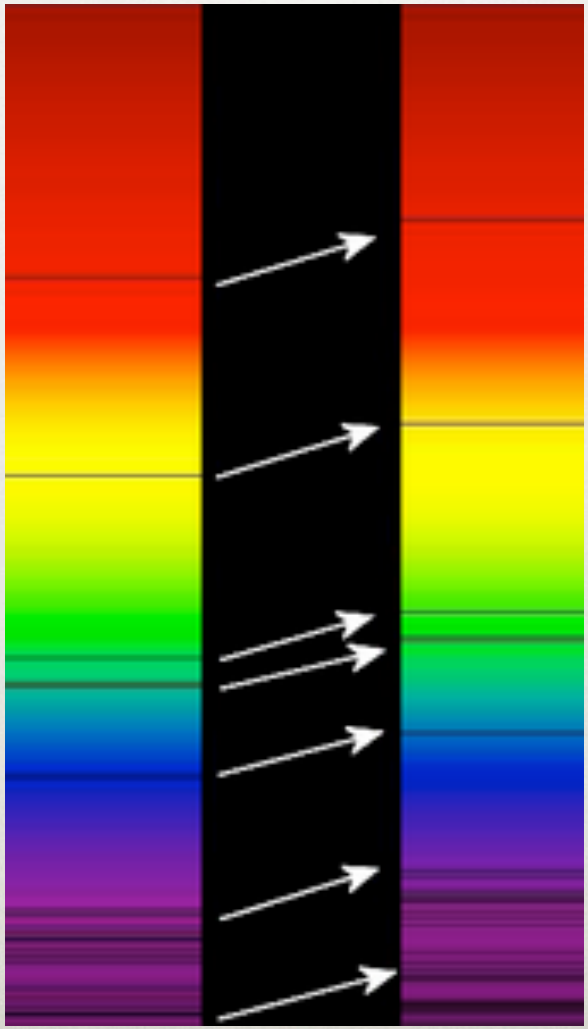
# Matter v. Radiation




Matter v. Dark Energy
25%
72%
(today)
96%!
times 2
(times 2)²

# OBSERVATIONS

# Redshift tells us amount of expansion



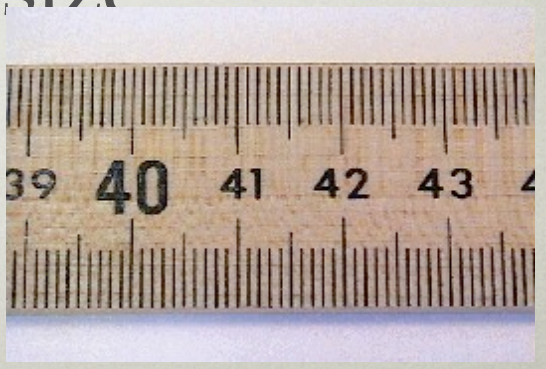
# Needed: another distance measurement

- **Luminosity distance**: known brightness

  ➡ *STANDARD CANDLE*

- **Angular size distance**: known size

  ➡ *STANDARD RULER*



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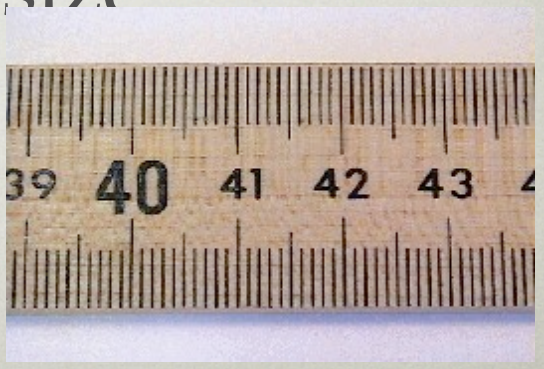
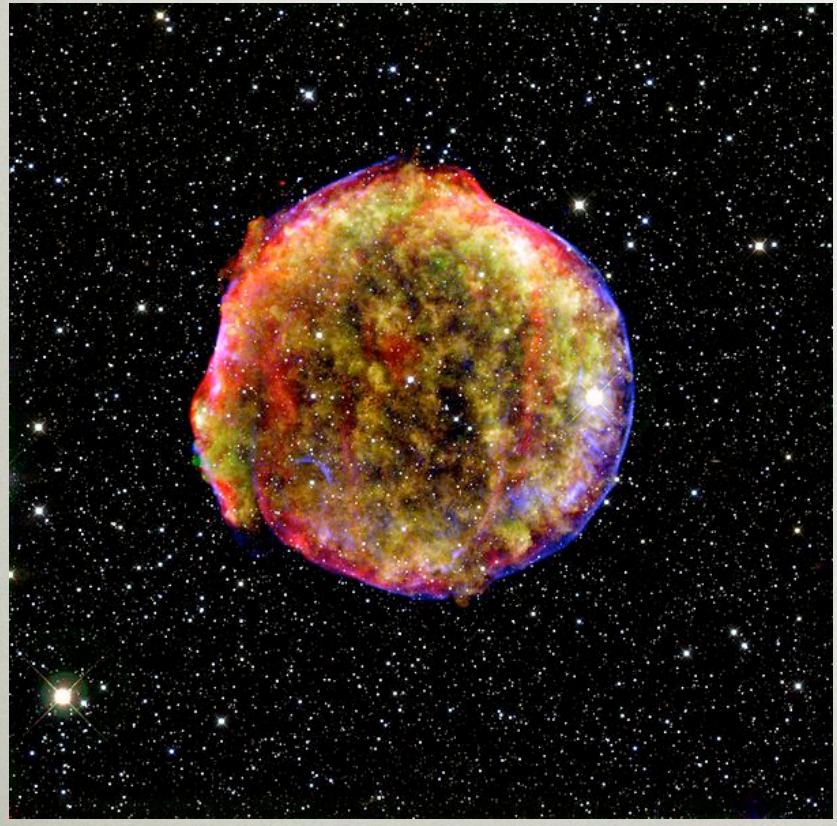
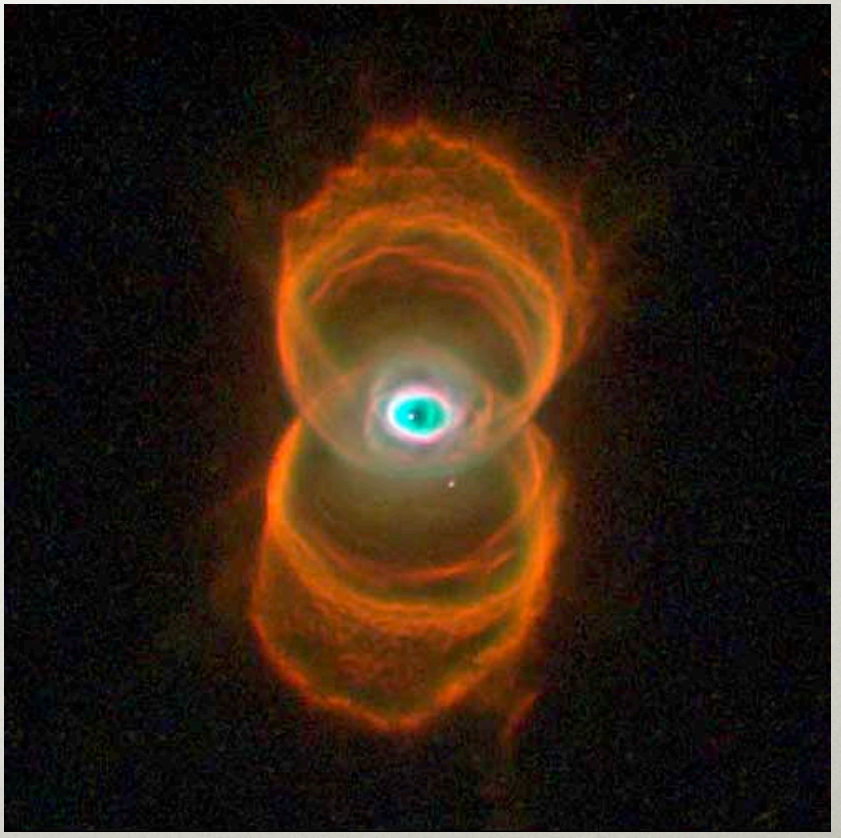


# Supernovae: main types

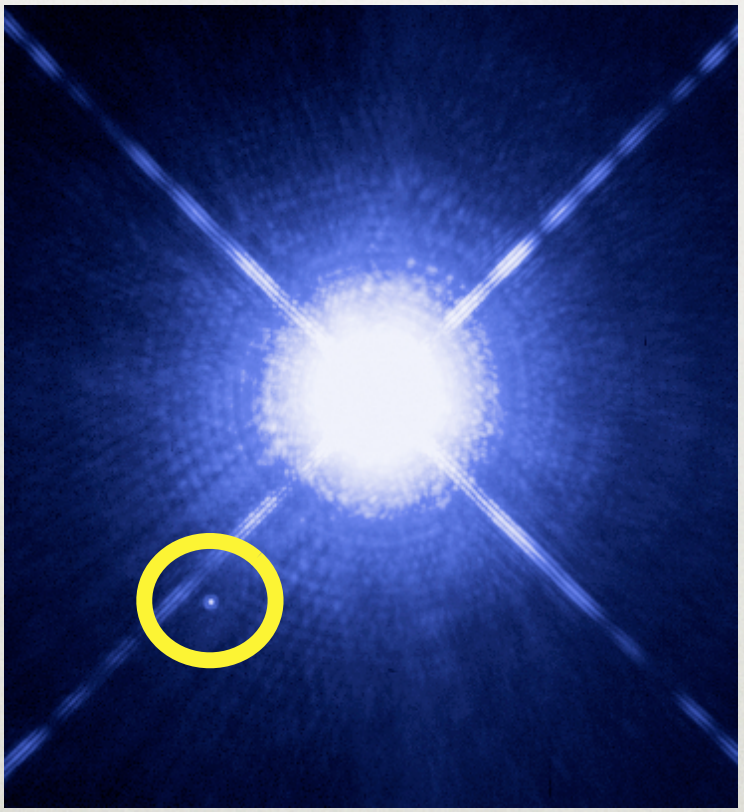
Ia



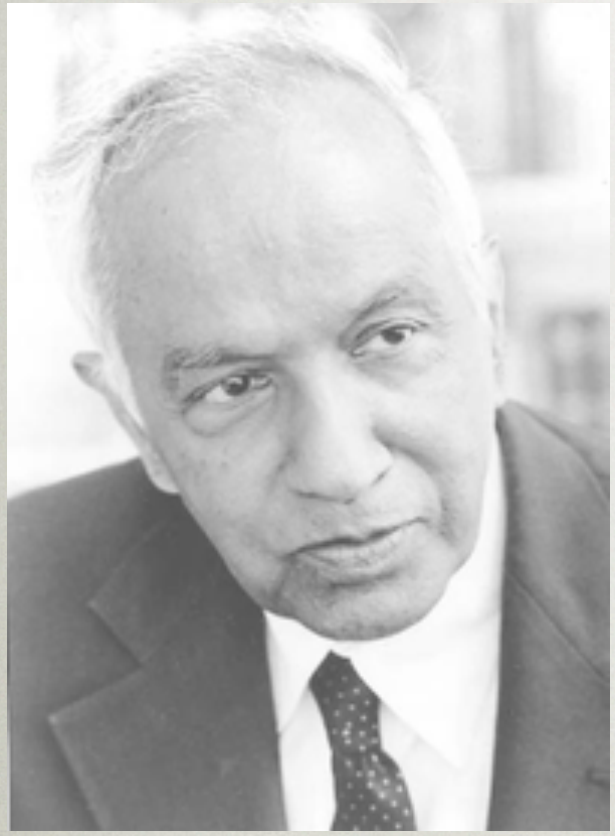
II



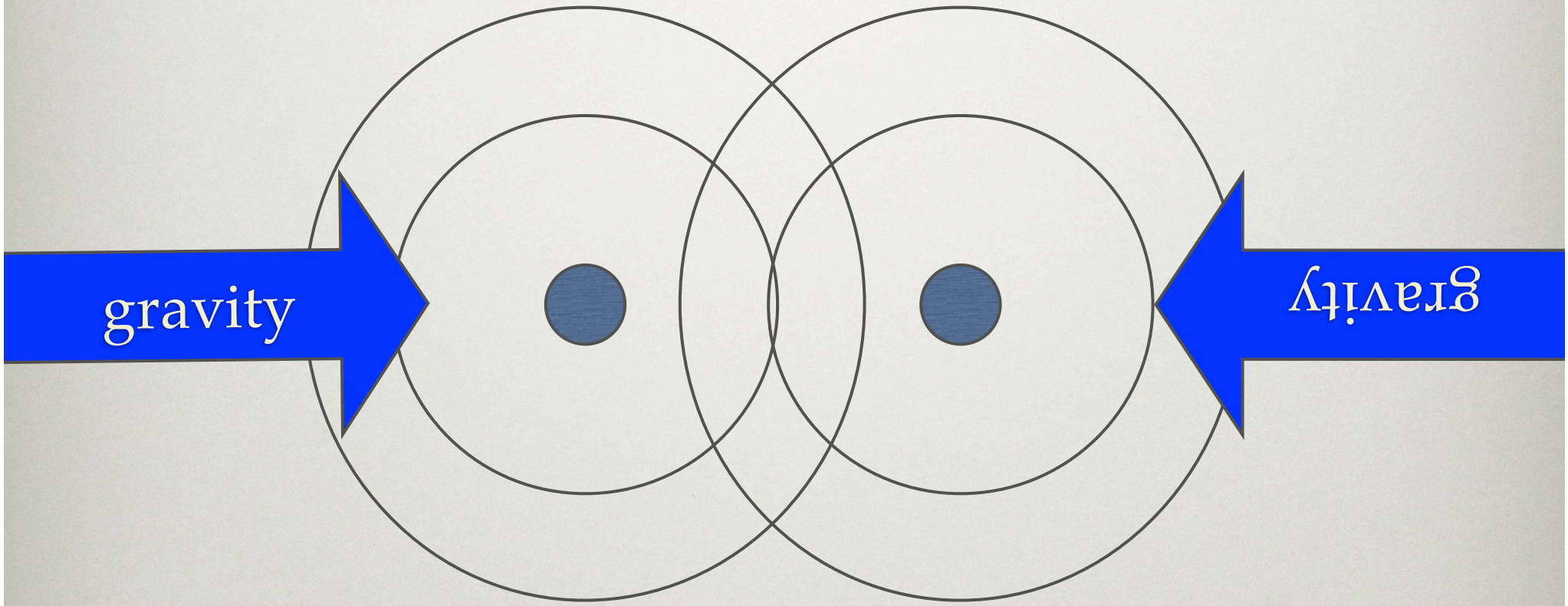
# SNe Ia: ex-white Dwarfs



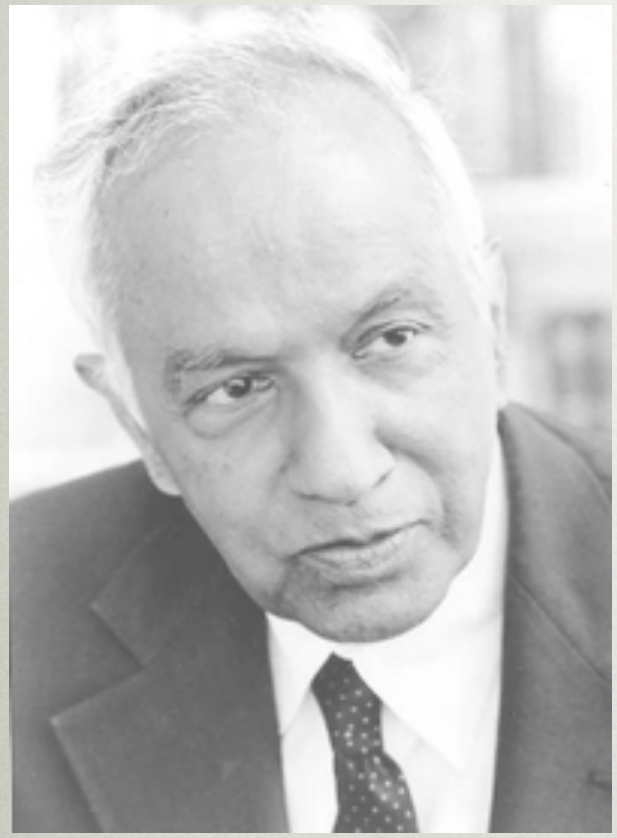
# Chandrasekhar Mass

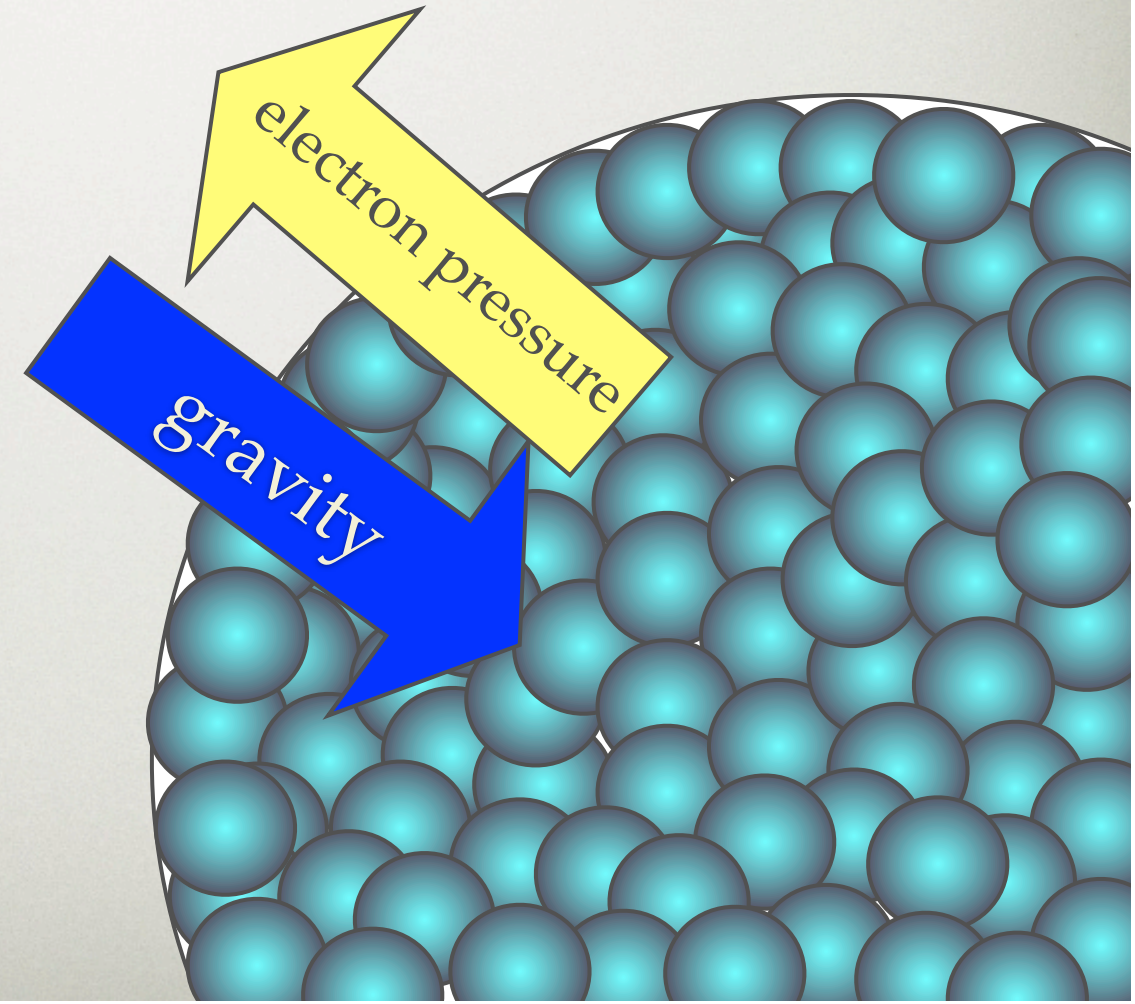


# Atoms getting too close for comfort

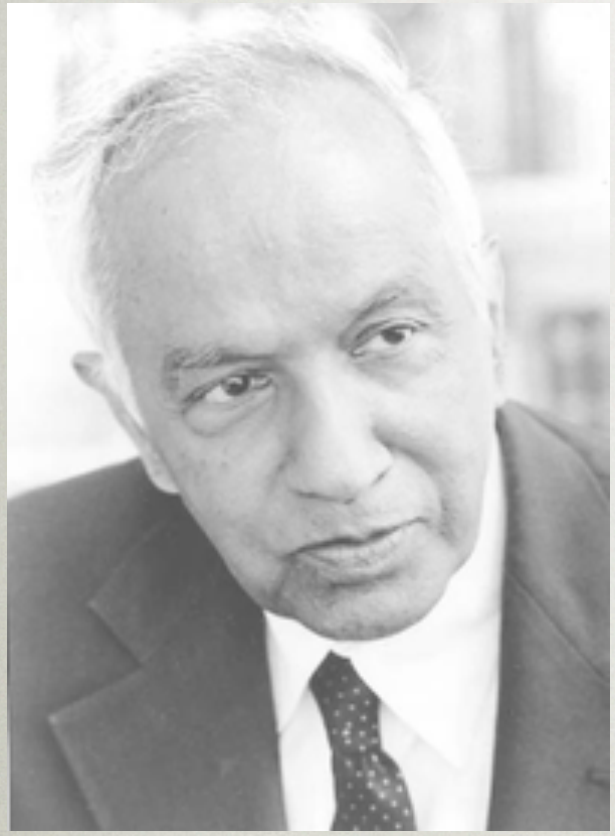


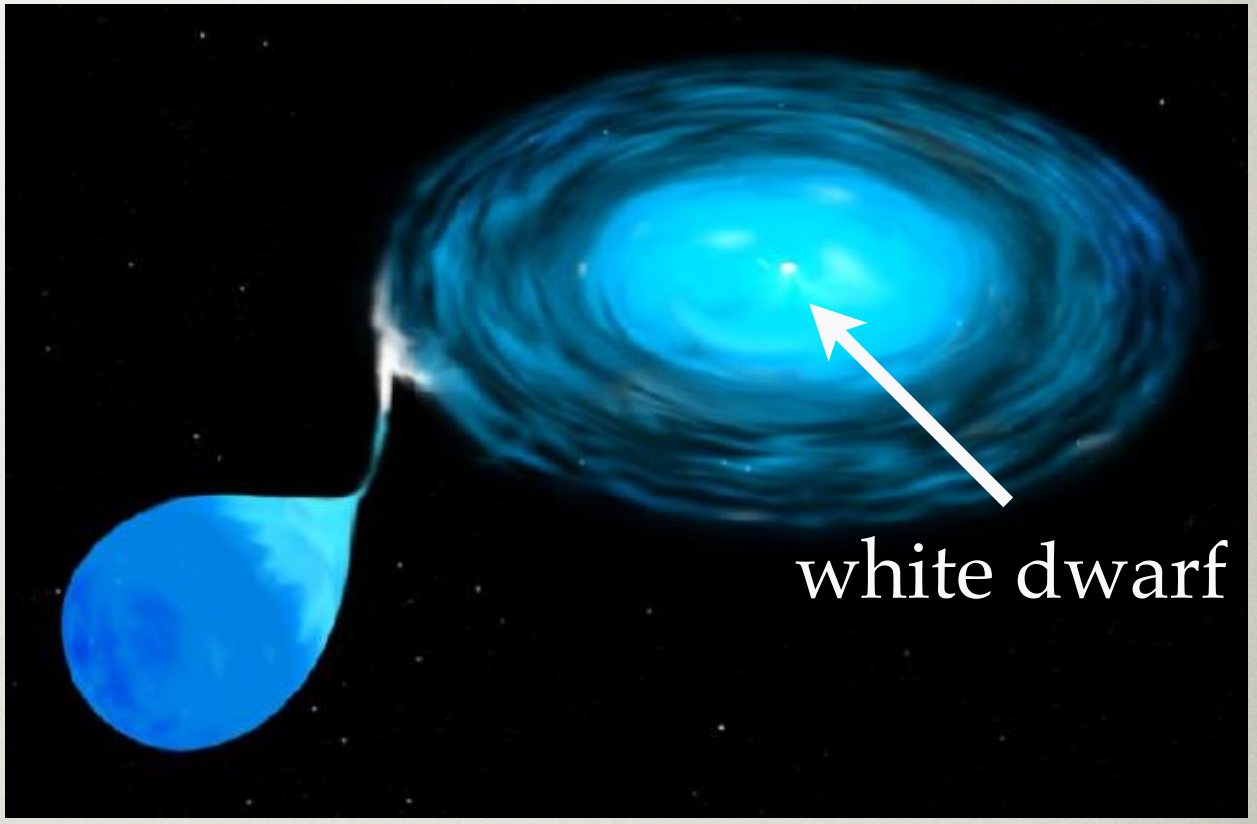
# Chandrasekhar Mass: 1.4 Solar Masses



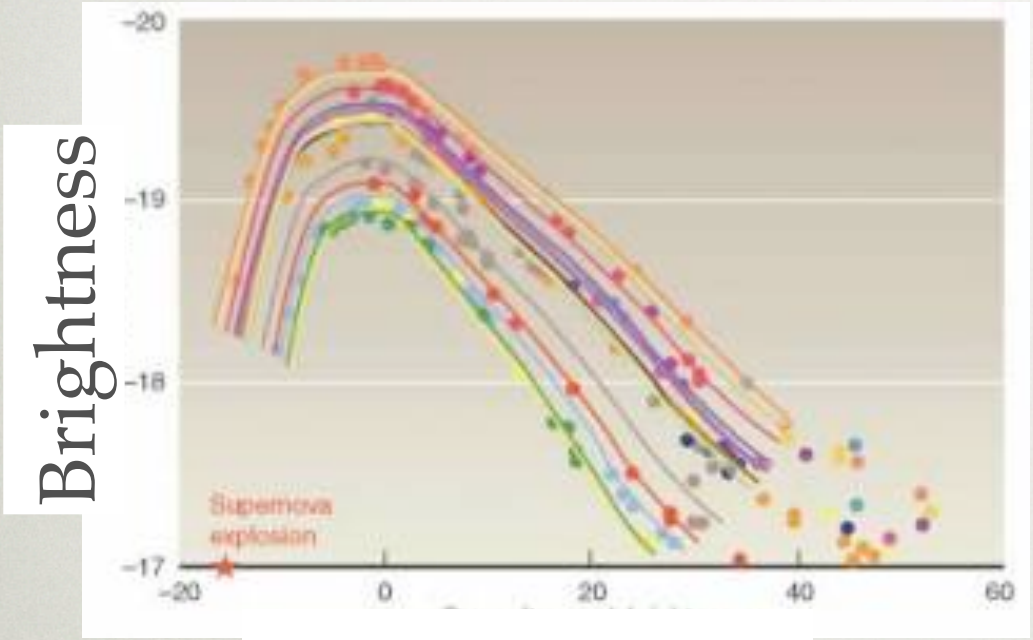


# Accretion gets you there





# SNe Ia: "standardizable" candle



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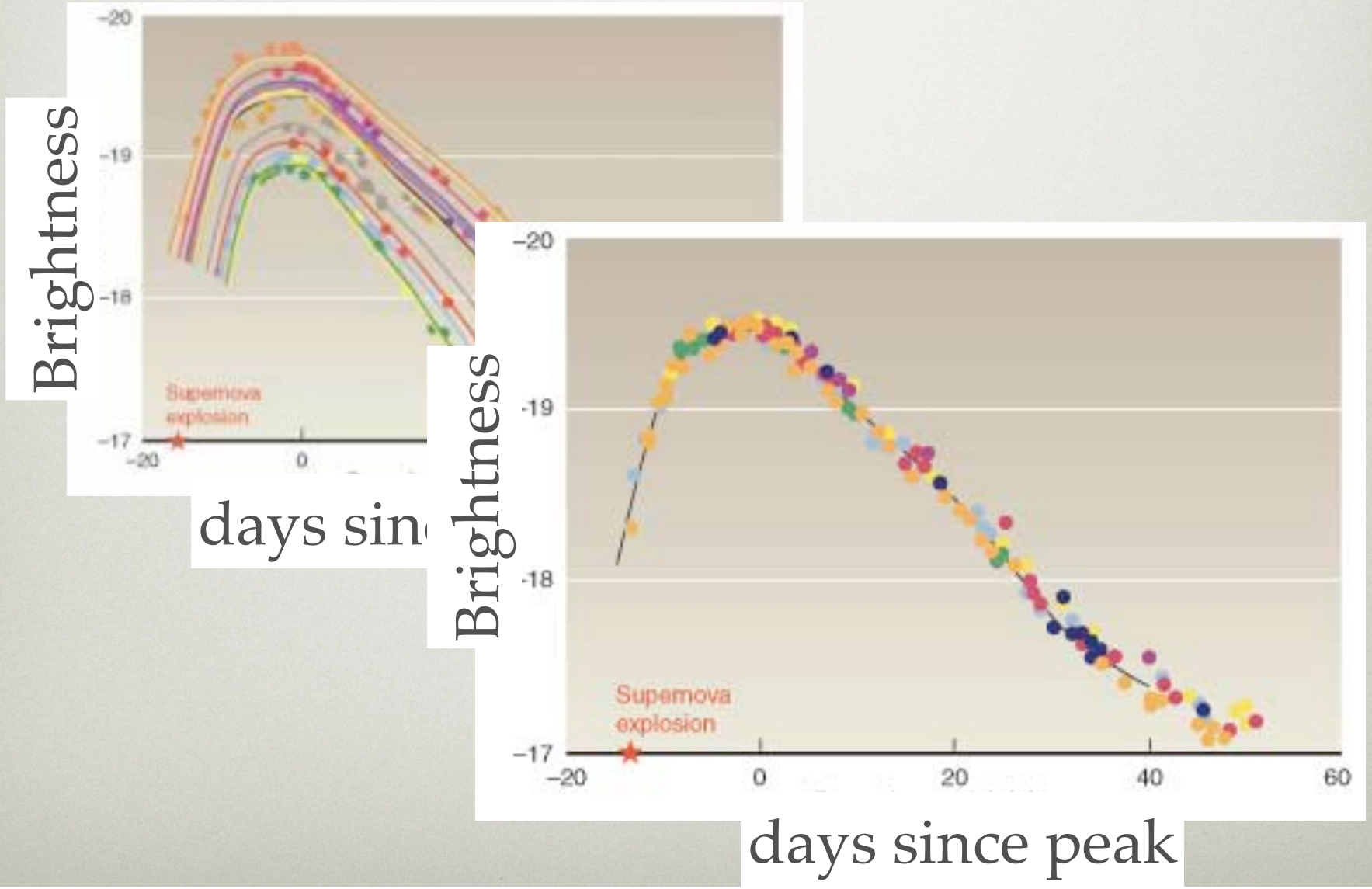
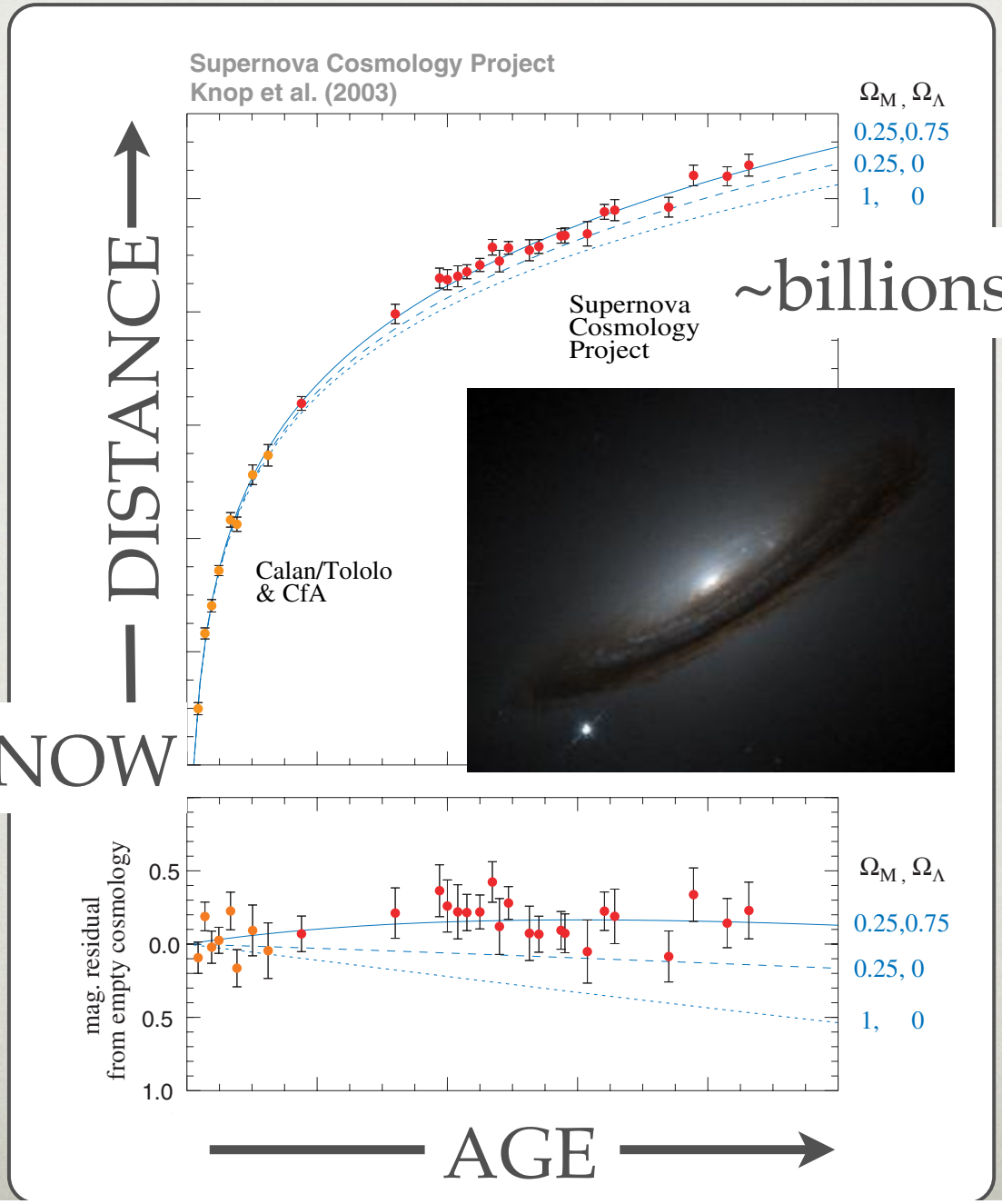


# Result: Expansion Rate is Accelerating

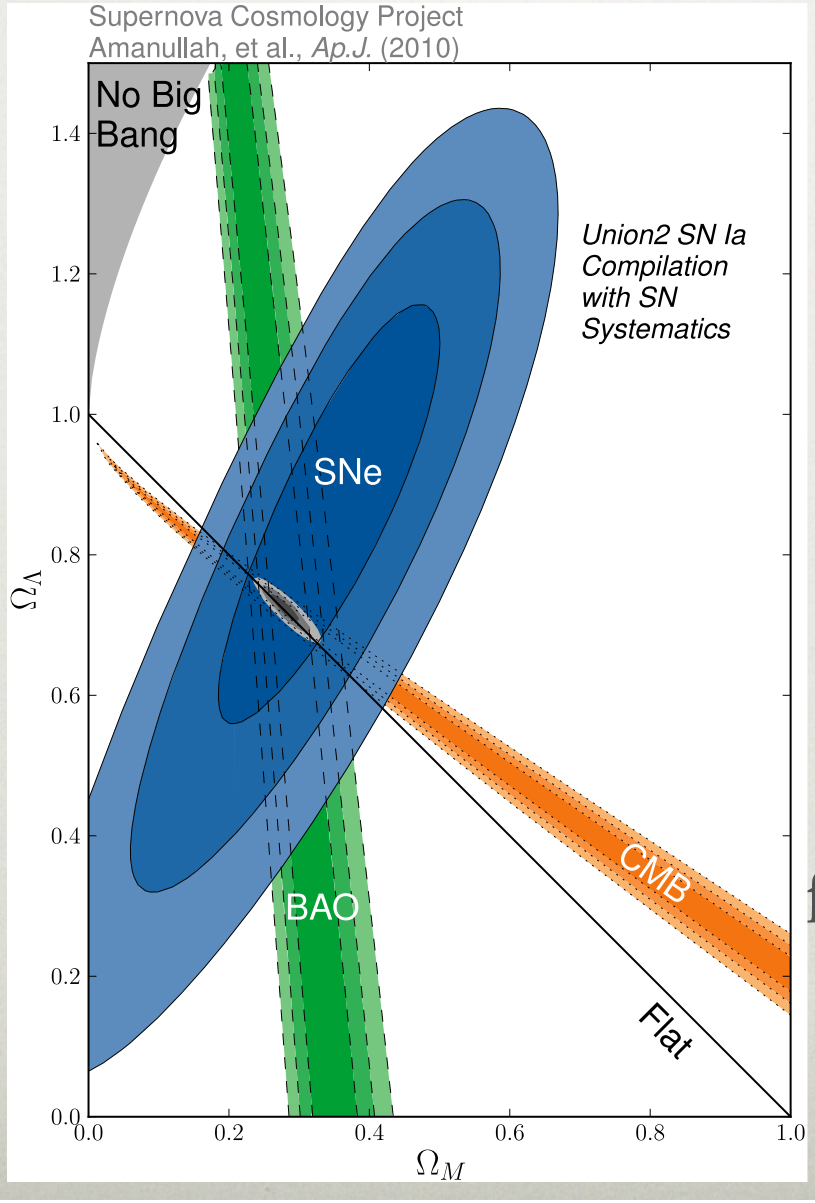



~billions of years ago

~2000

# Not Just Supernovae

# Other Dark energy observations




from the Supernova Cosmology Project (Perlmutter et al)

# Theory says?

# We don't understand acceleration

$$\frac{\text{theoretical prediction}}{\text{observed value}} \sim 10^{121}$$

# So: what is $\Lambda$?

- Observed:

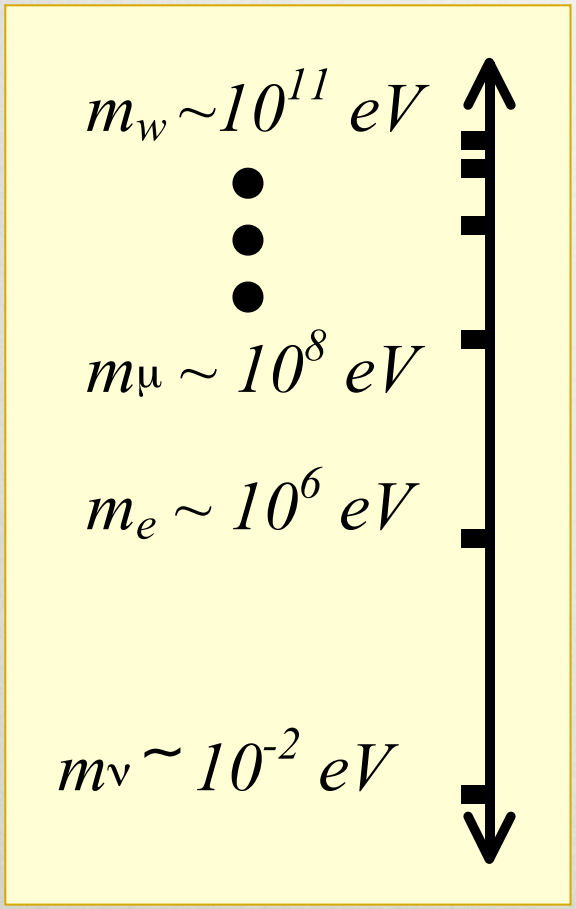
$$\rho_\Lambda = \frac{\mu^4}{\hbar^3 c^5} \simeq 10^{-29} g/cm^3$$

- Implies...

$$\mu \simeq 10^{-2} eV$$

- Problem because ...

# The Cosmological Constant Problem

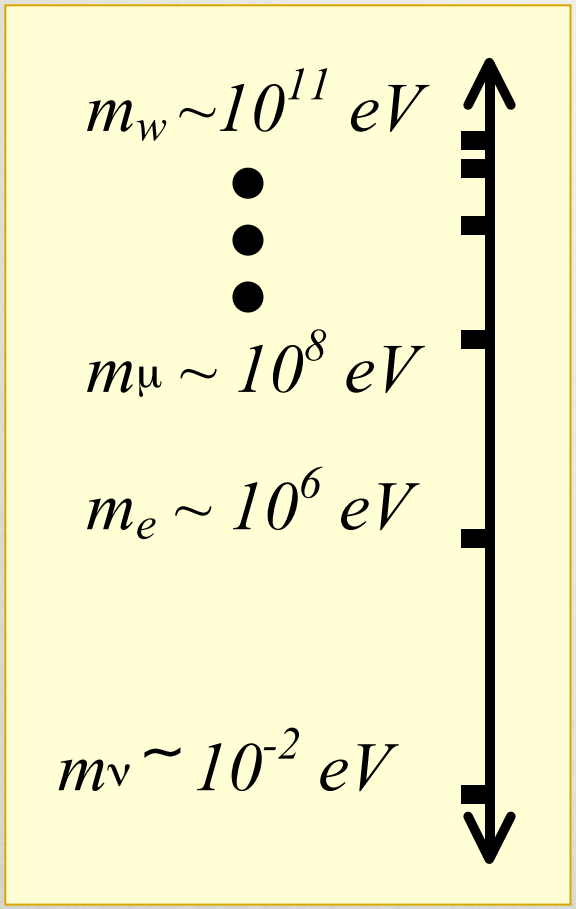



Particles of mass $m$ should make effective $\mu \gg m$:

$$\rho \simeq (10^{-2} eV)^4$$

(argument from Cliff Burgess)

# The Cosmological Constant Problem




Particles of mass $m$ should make effective $\mu \gg m$:

$$\rho \approx \rho_0 + k_\nu m_\nu^4$$

$$\rho \simeq (10^{-2} eV)^4$$

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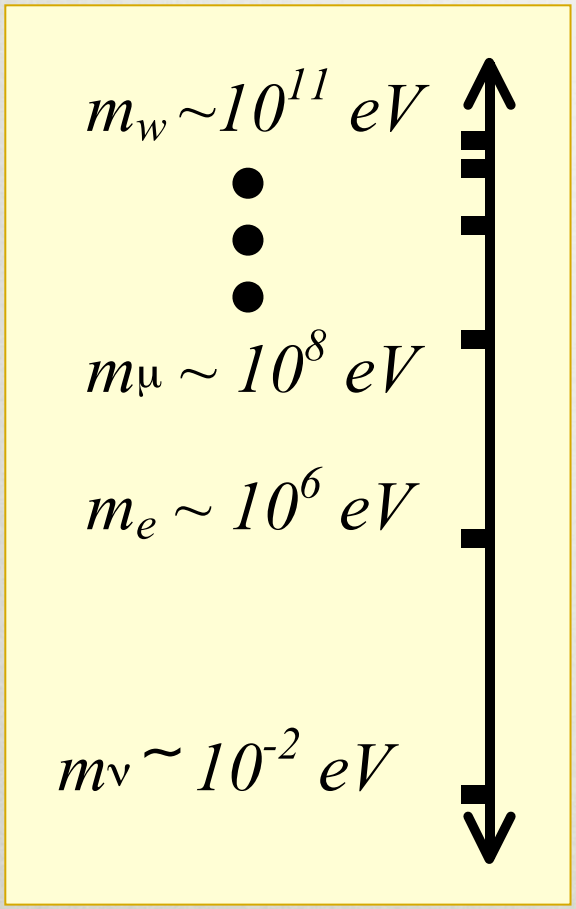



Particles of mass $m$ should make effective $\mu \gg m$:

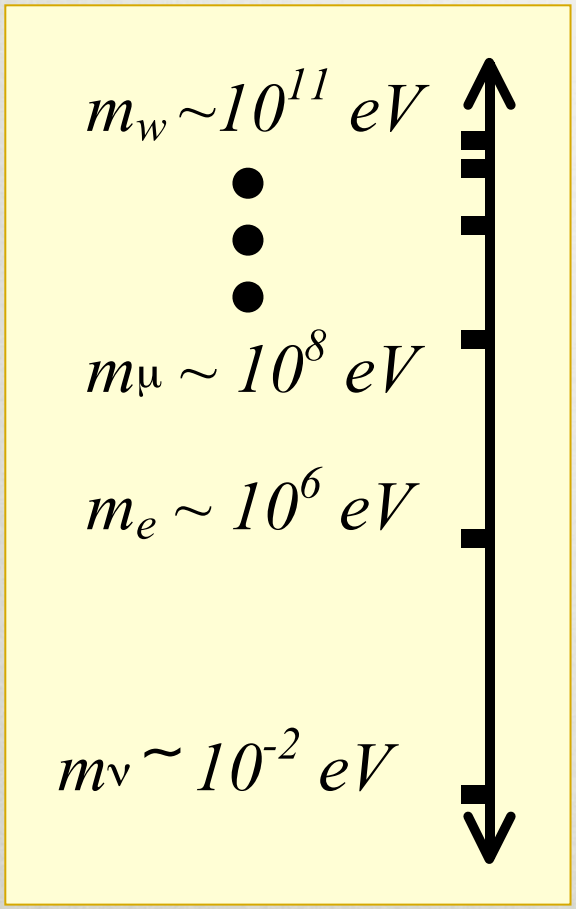
$$\rho \approx \rho_1 + k_e m_e^4 + k_\nu m_\nu^4$$

$$\rho \approx \rho_0 + k_\nu m_\nu^4$$

$$\rho \simeq (10^{-2} eV)^4$$

(argument from Cliff Burgess)

# The Cosmological Constant Problem




Particles of mass $m$ should make effective $\mu \gg m$:

$$\rho \approx \rho_1 + k_e m_e^4 + k_\nu m_\nu^4$$

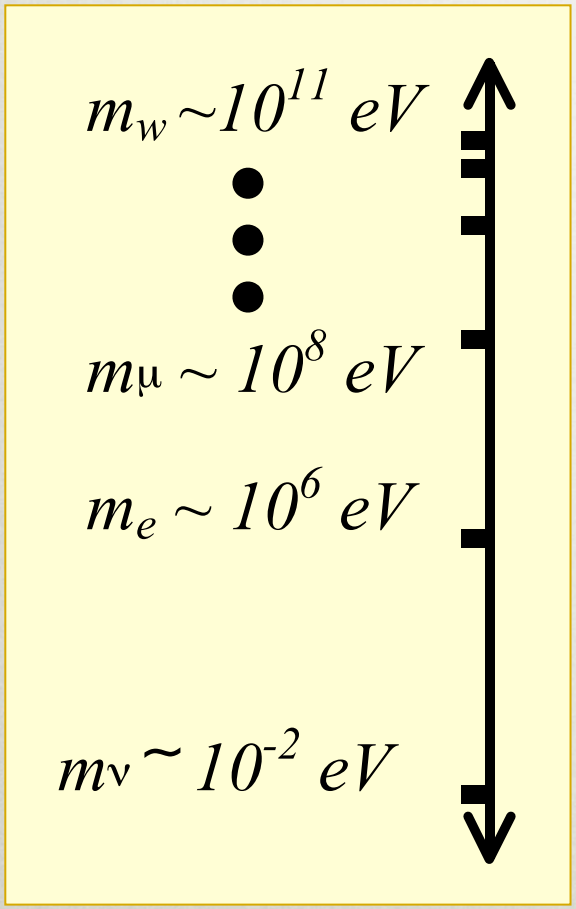
$$\rho \approx \rho_0 + k_{\quad} m^4$$

$$\rho \simeq (10^{-}$$

*Must cancel to 32 decimal places!!*

(argument from Cliff Burgess)

# The Cosmological Constant Problem




Particles of mass $m$ should make effective $\mu \gg m$:

$$\rho \approx \rho_2 + k_\mu m_\mu^4 + k_e m_e^4 + \ldots$$

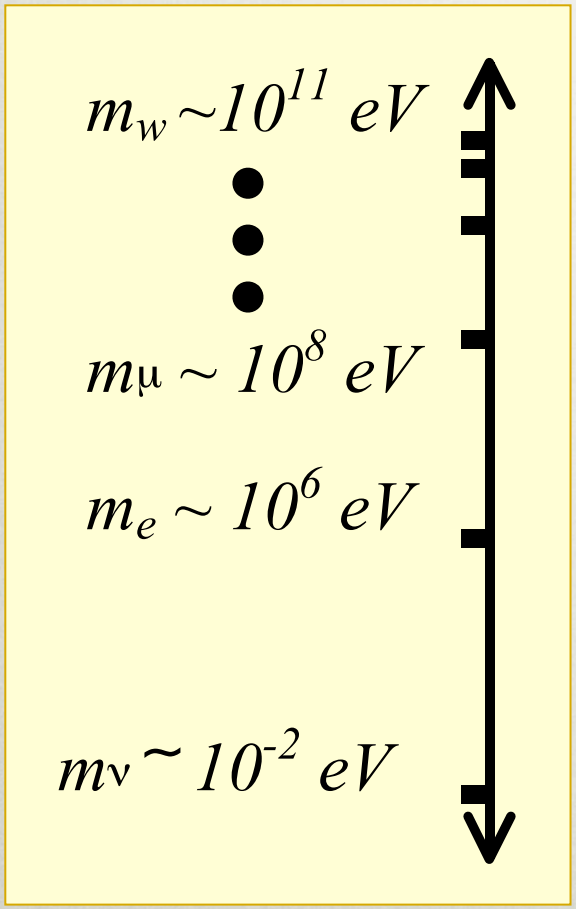
$$\rho \approx \rho_1 + k_e m_e^4 + k_\nu m_\nu^4$$

$$\rho \approx \rho_0 + k_\nu m_\nu^4$$

$$\rho \simeq (10^{-2} eV)^4$$

(argument from Cliff Burgess)

# The Cosmological Constant Problem




Particles of mass $m$ should make effective $\mu \gg m$:

$$\rho \approx \rho_2 + k_\mu m_\mu^4 + k_e m_e^4 + \ldots$$

$$\rho \approx \rho_1 + k_e m_e^4 + k_\nu m_\nu^4$$

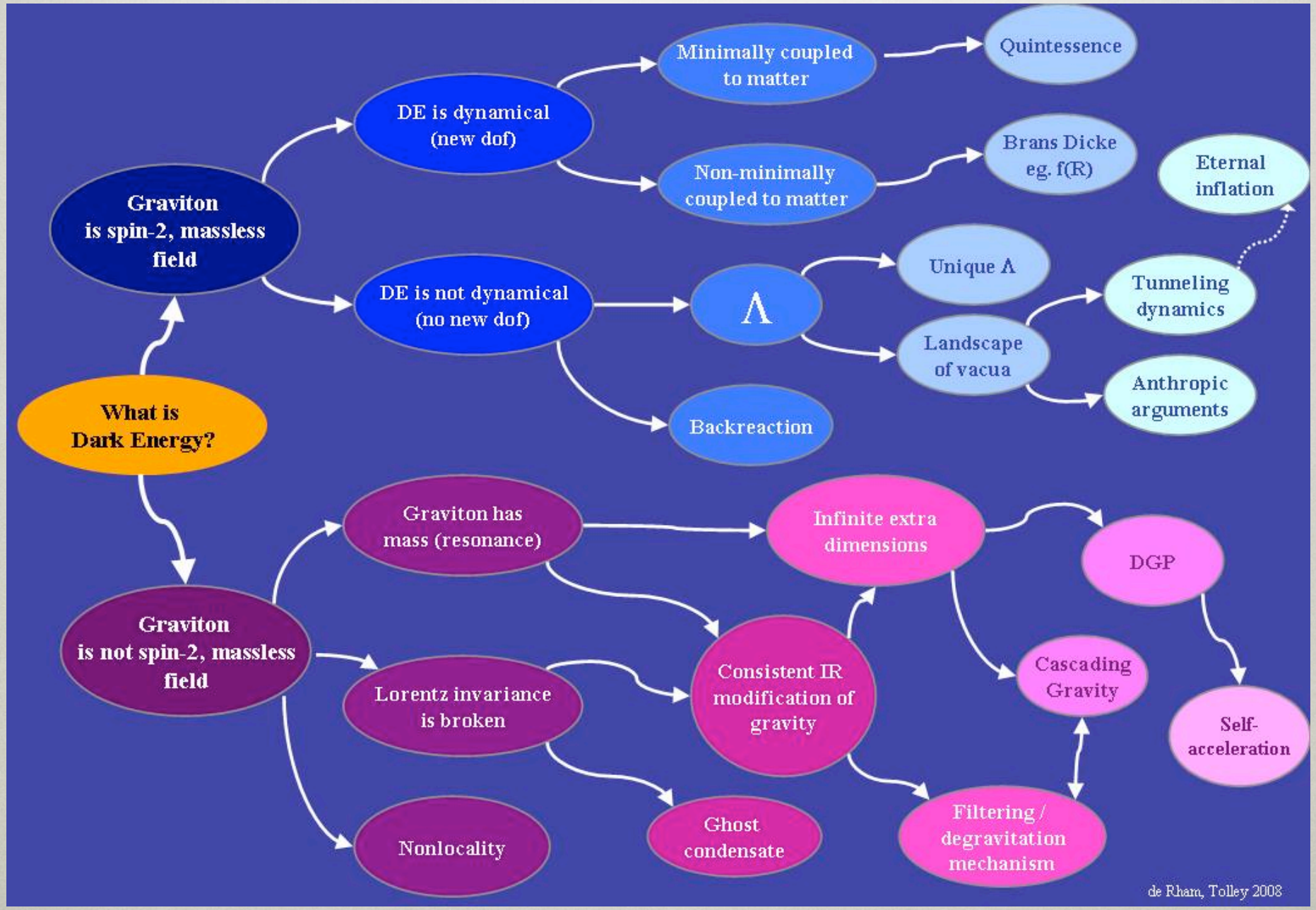
$$\rho \approx \rho_0 + k_\nu m_\nu^4$$

$$\rho \simeq (10^{-}$$

*Must cancel to 40 decimal places!!*

(argument from Cliff Burgess)

# Many attempted solutions:



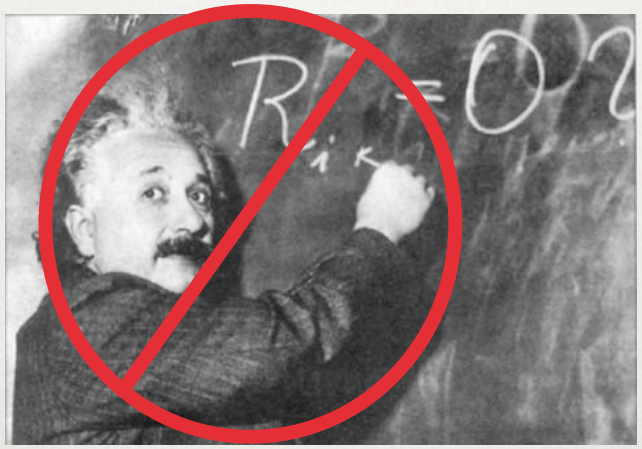

Taken from: Claudia de Rham and Andrew J. Tolley, ``The Cosmological Constant Challenge" Nordita summer school on de Sitter Cosmology, 9-17 August 2008, to appear

# Many ideas, none clearly right:

# crisis!

# Main Possibilities

$\Lambda$



?

anthropic principle?

new predictions

?

# Our hopes

That observations will show:

1. Dark energy isn't exactly constant

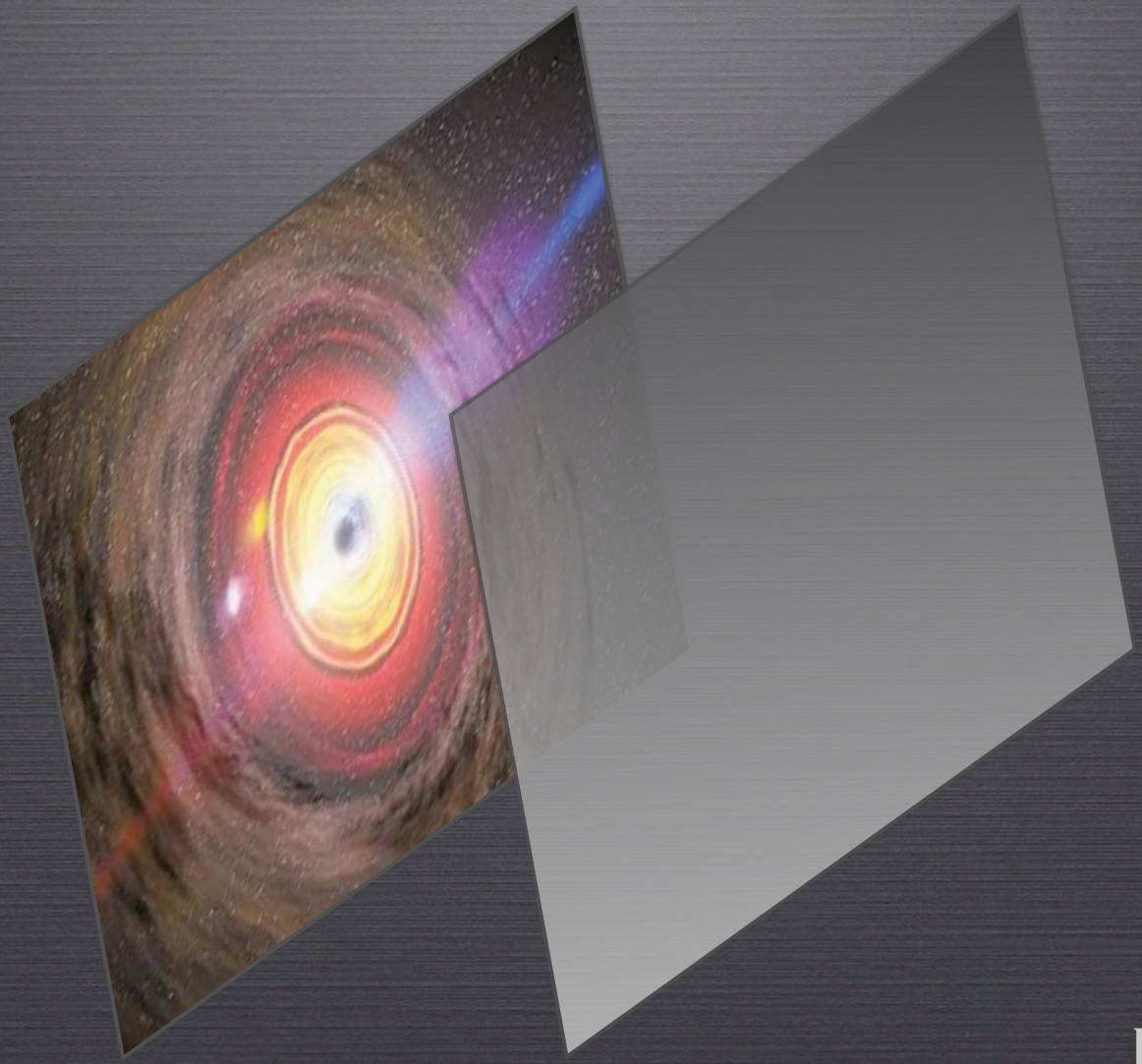
   (or)

2. A clear deviation from General Relativity will show up -- something, anything!

# What's next?

# Braneworld

## Speculations in Cosmology I



Lecture 7

# Massive Gravity

## Speculations in Cosmology II

W. Pauli

M. Fierz

$$m_g \neq 0?$$

Lecture 8