Dark Energy in the Universe

Islamabad

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a brief history

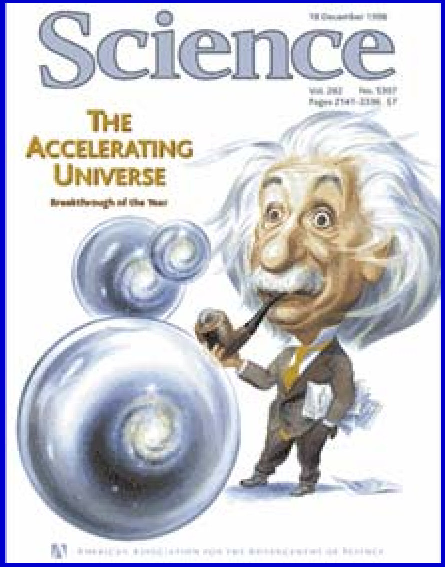
1910s – 1920s
Einstein: the universe must be static
introduce Λ to make it static

1920s – 1930s
Hubble: the universe is expanding
Friedman-Lemaitre model – discard Λ

1940s – 1960s: cosmology as maths

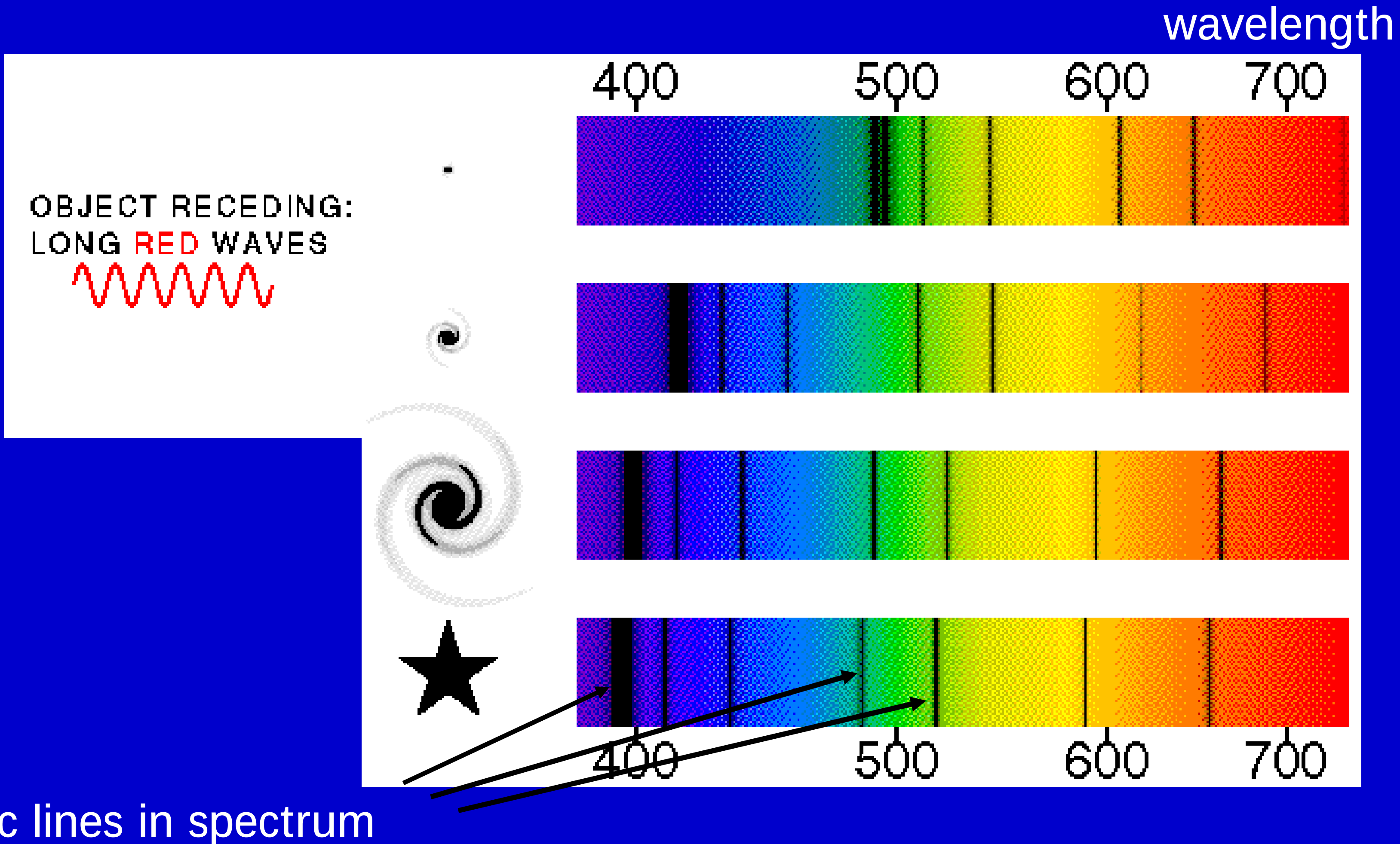
1970s – 1990s: cosmology as physics
standard model – the universe is expanding
but slowing down

late 1990s: revolution
observations – the universe is accelerating!
theory – restore Λ to make it accelerate



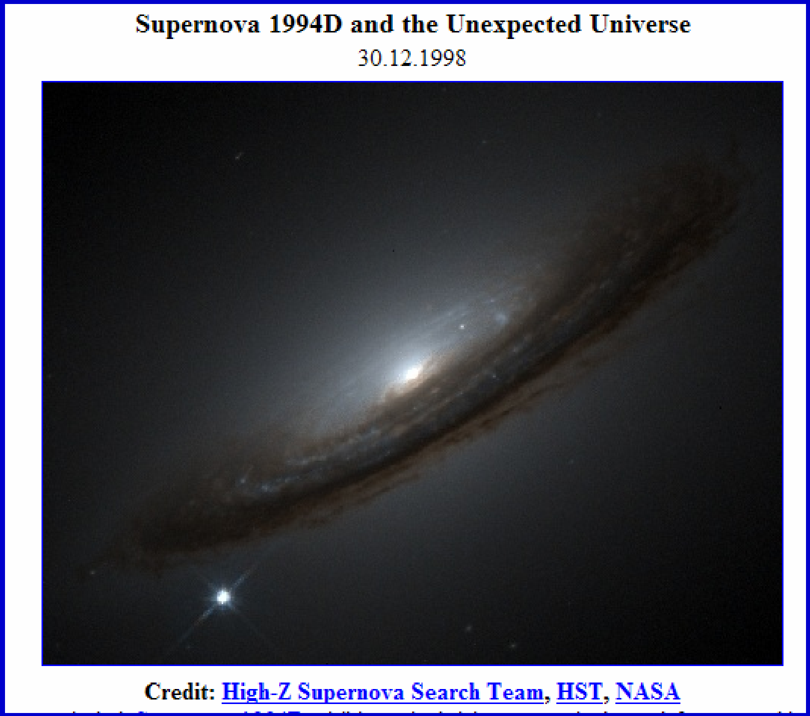
the key evidence for expansion:

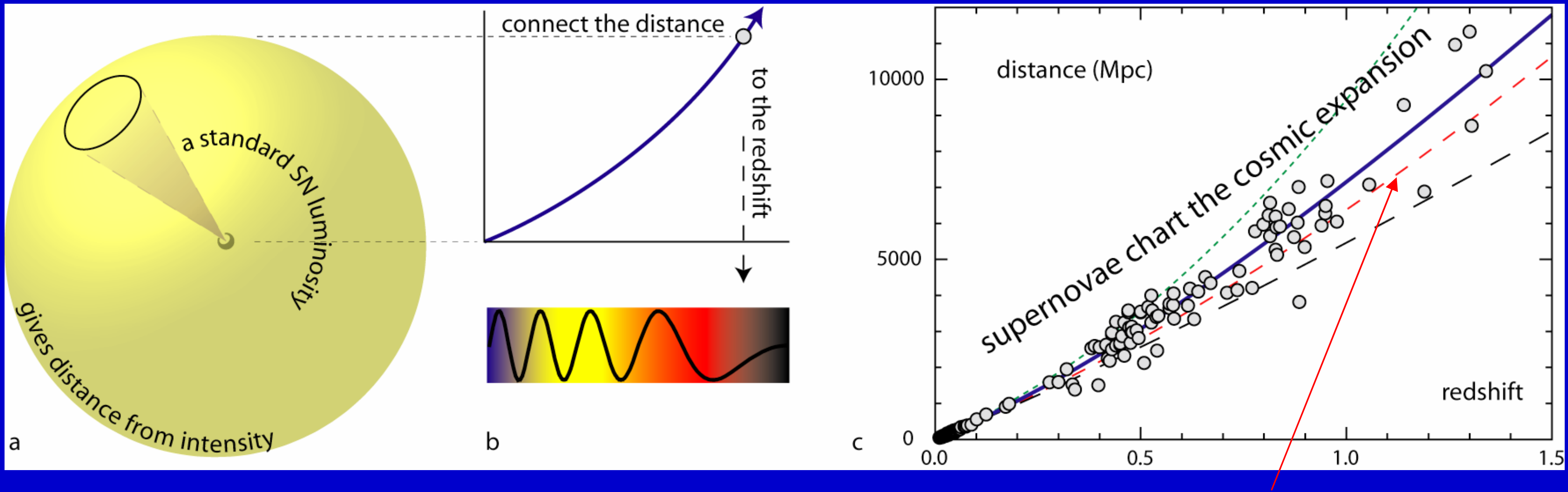
redshift of galaxies



the key evidence for acceleration:

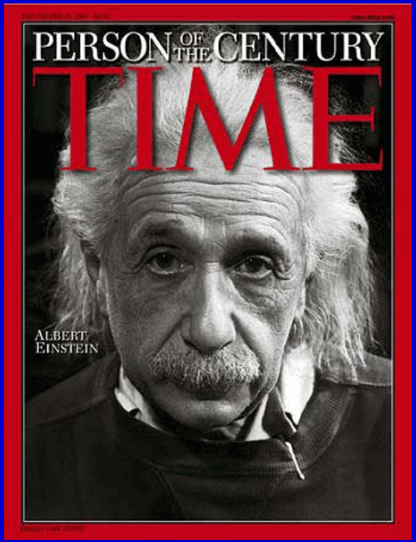
supernovae are more dim than they should be



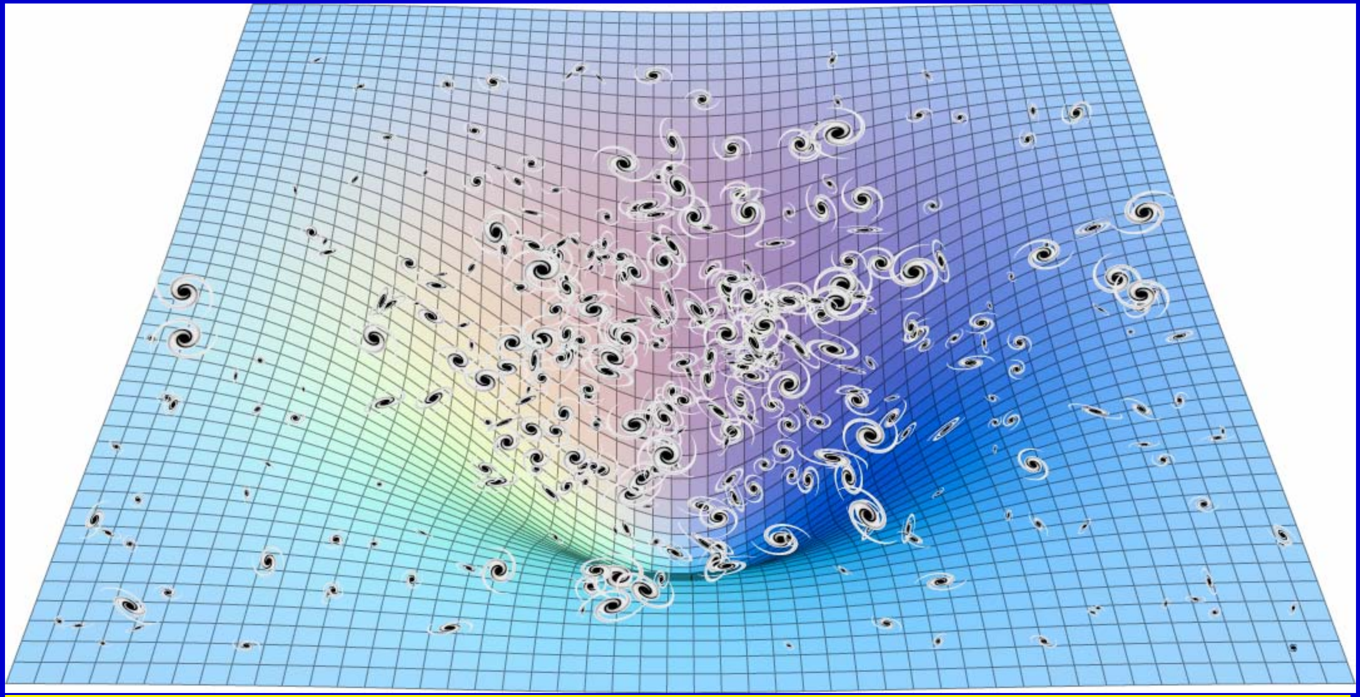


zero-acceleration curve

Einstein's theory of gravity



spacetime tells matter how to move
&
matter tells spacetime how to curve

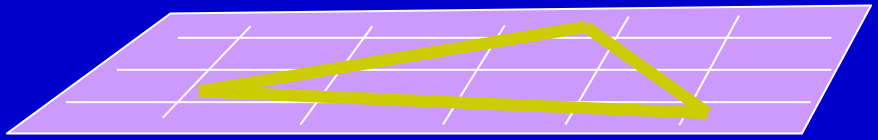


$$G_{\mu\nu}\ (\text{spacetime geometry}) = \frac{8\pi G}{c^4} T_{\mu\nu}\ (\text{matter - energy})$$

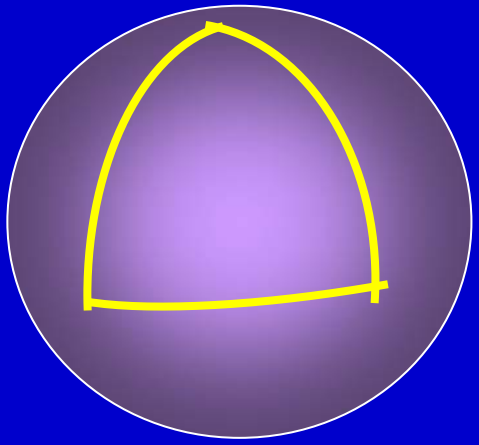
the geometry of curved space

Riemannian geometry = curved space

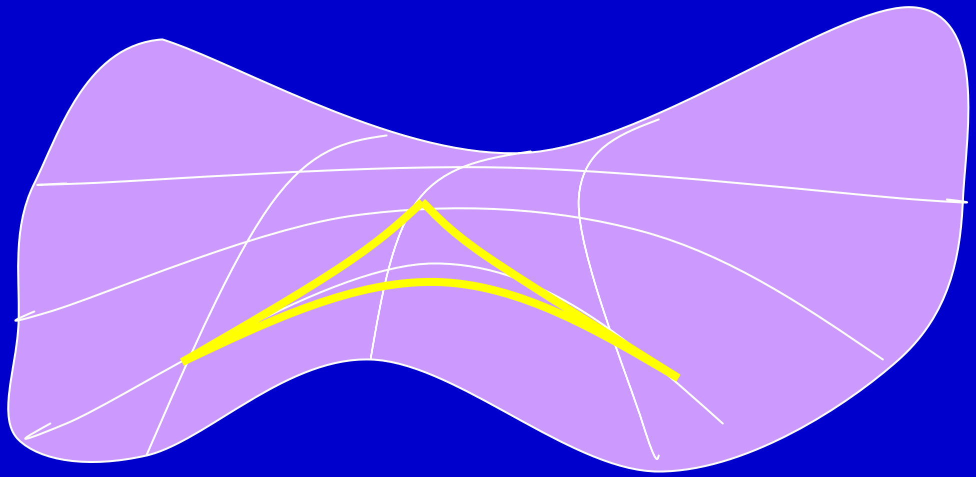
flat $\alpha + \beta + \gamma = 180^o$



spherical (closed)



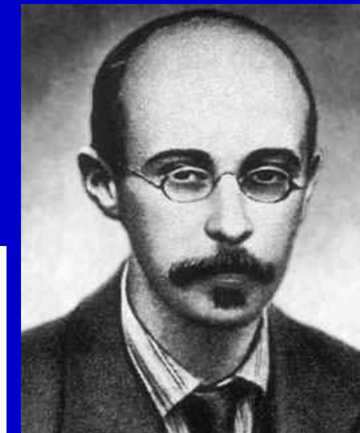
$\alpha + \beta + \gamma > 180^o$



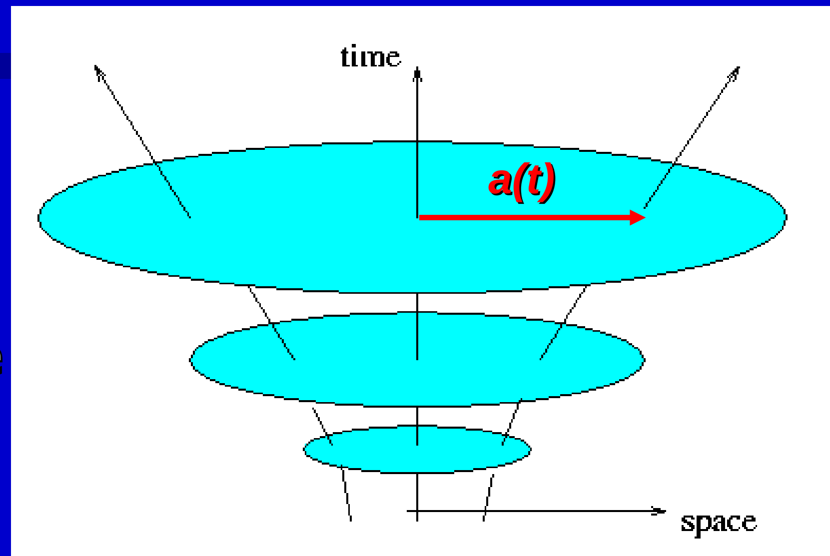
hyperbolic (open)

$\alpha + \beta + \gamma < 180^o$

Friedman's expanding universe



each time instant =
3D space
of constant curvature

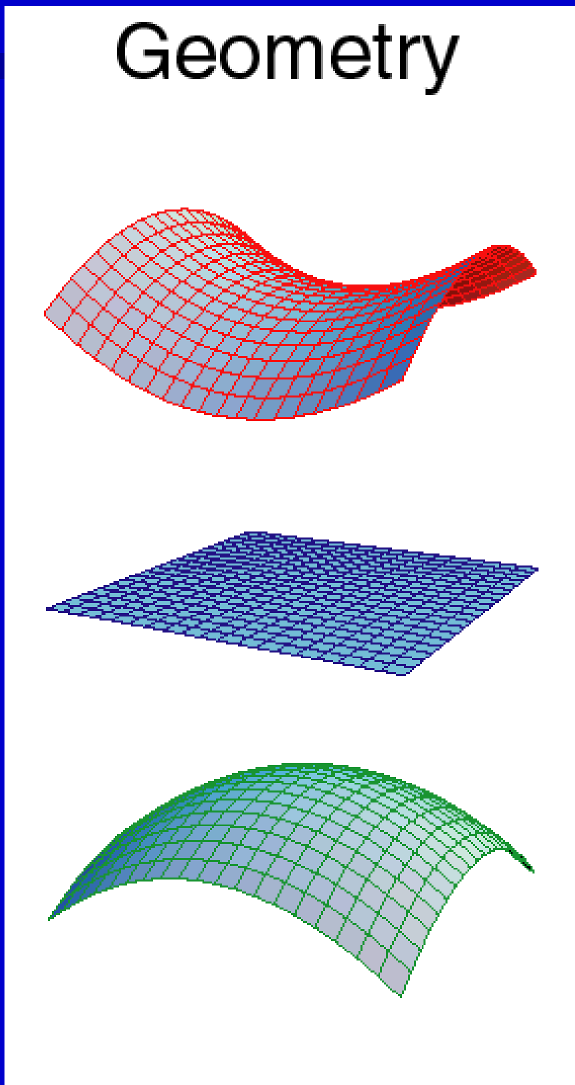


Friedman equation:

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}(\rho_m + \rho_r) + \frac{\Lambda}{3} - \frac{K}{a^2}$$

expansion rate = matter/radiation + dark energy + curvature

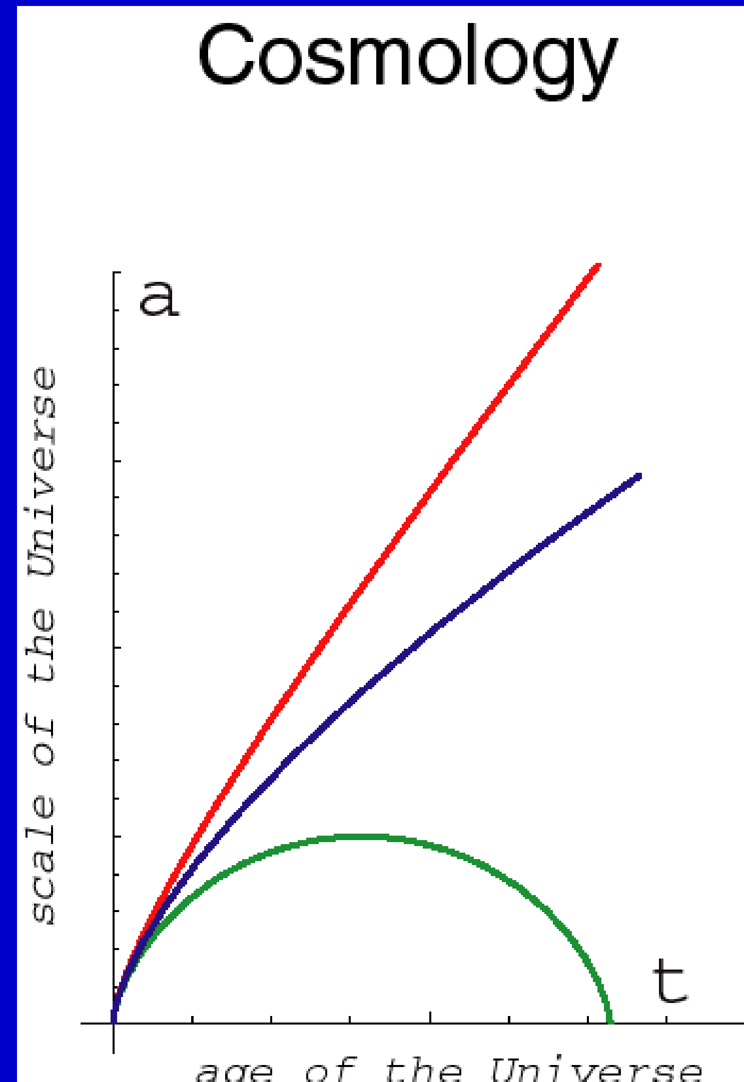
solutions of Friedman equation: Λ=0



K=1

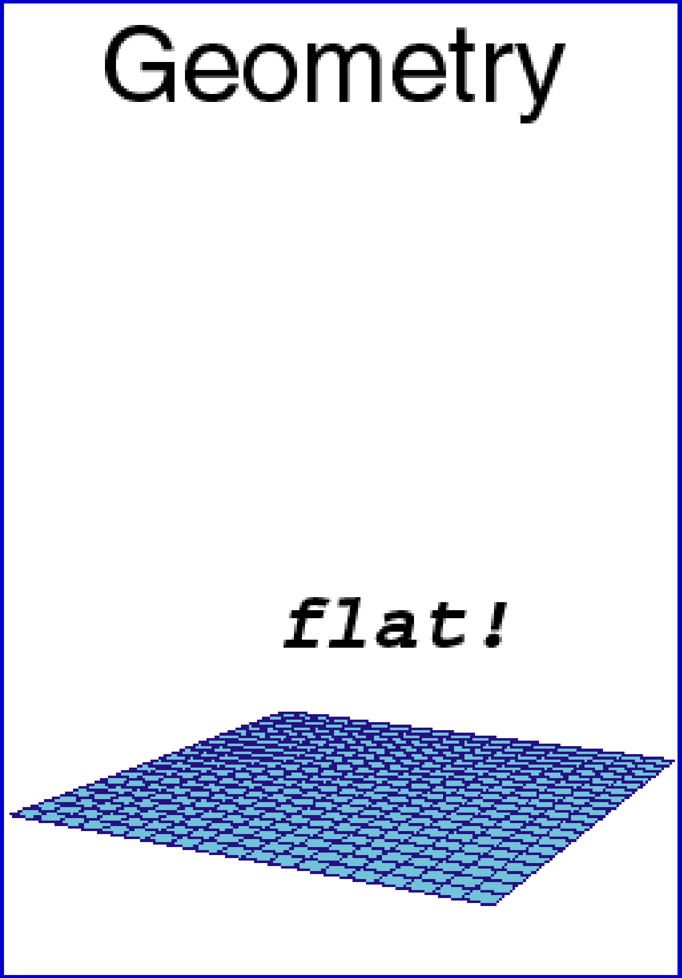
K=0

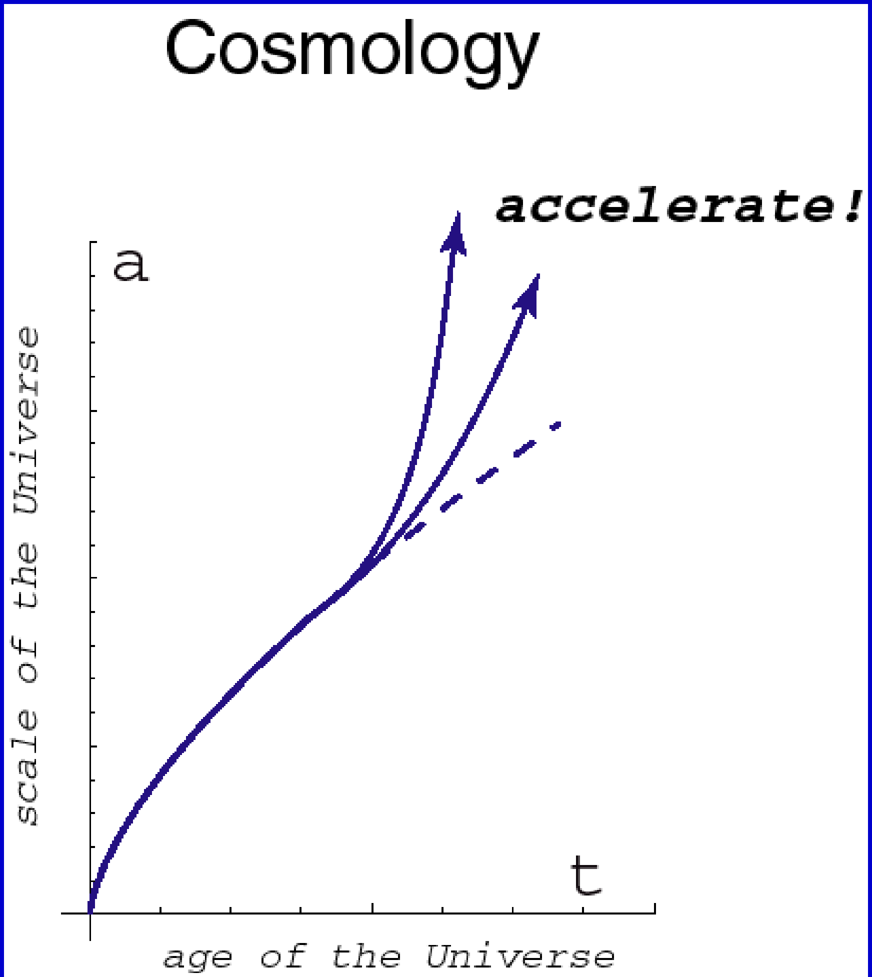
K=-1



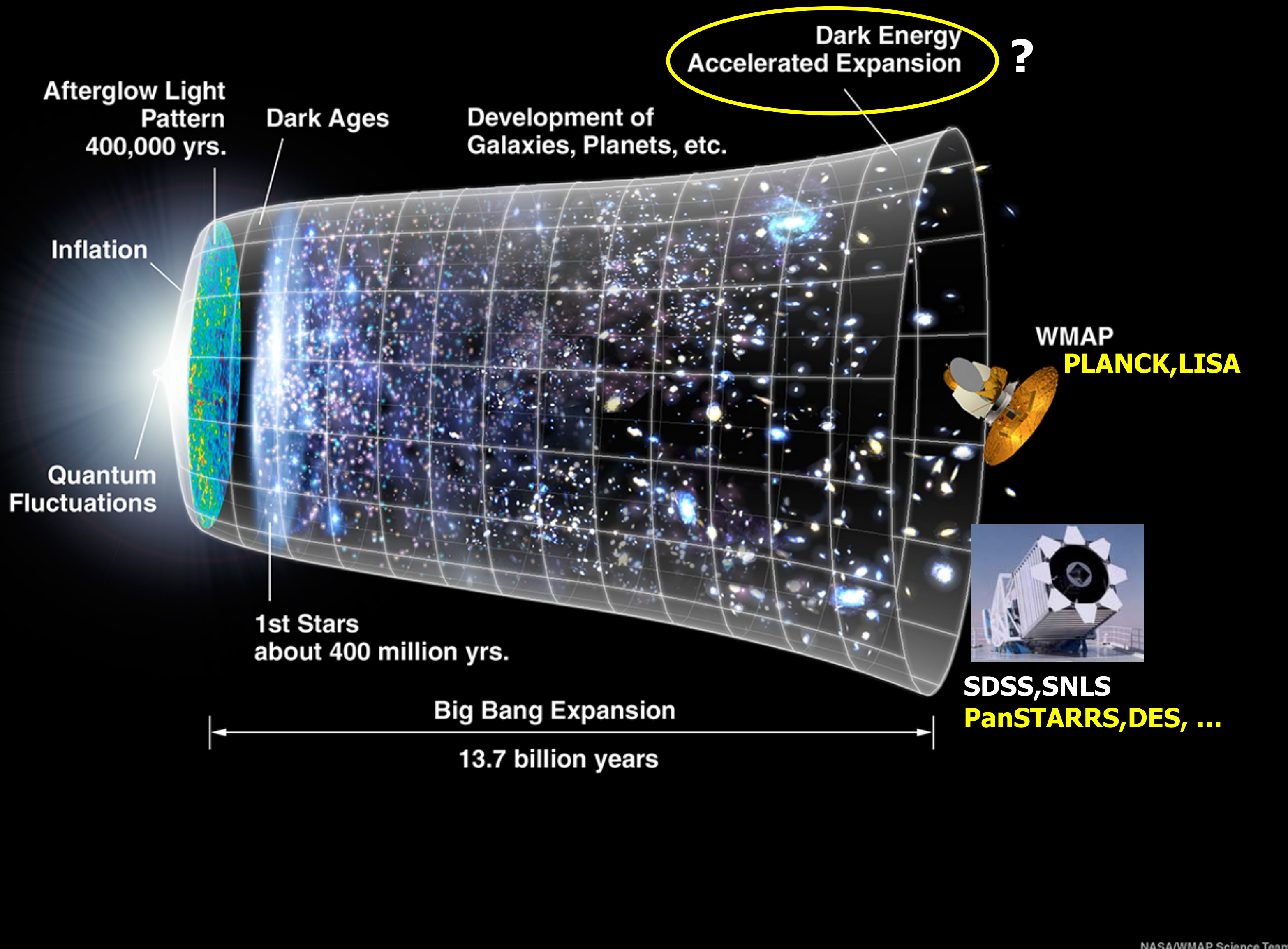
solutions of Friedman equation: Λ>0

observations: K=0

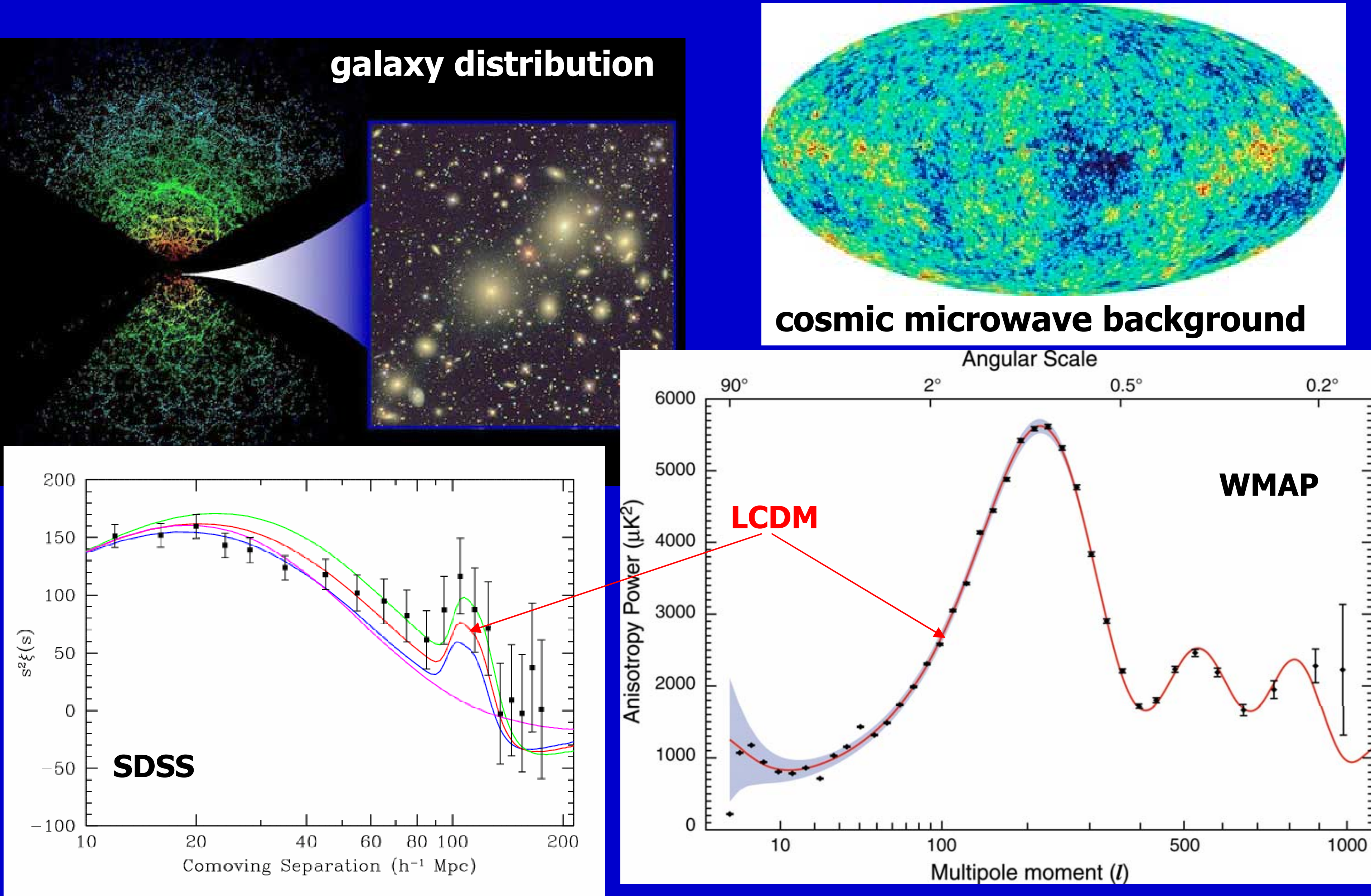




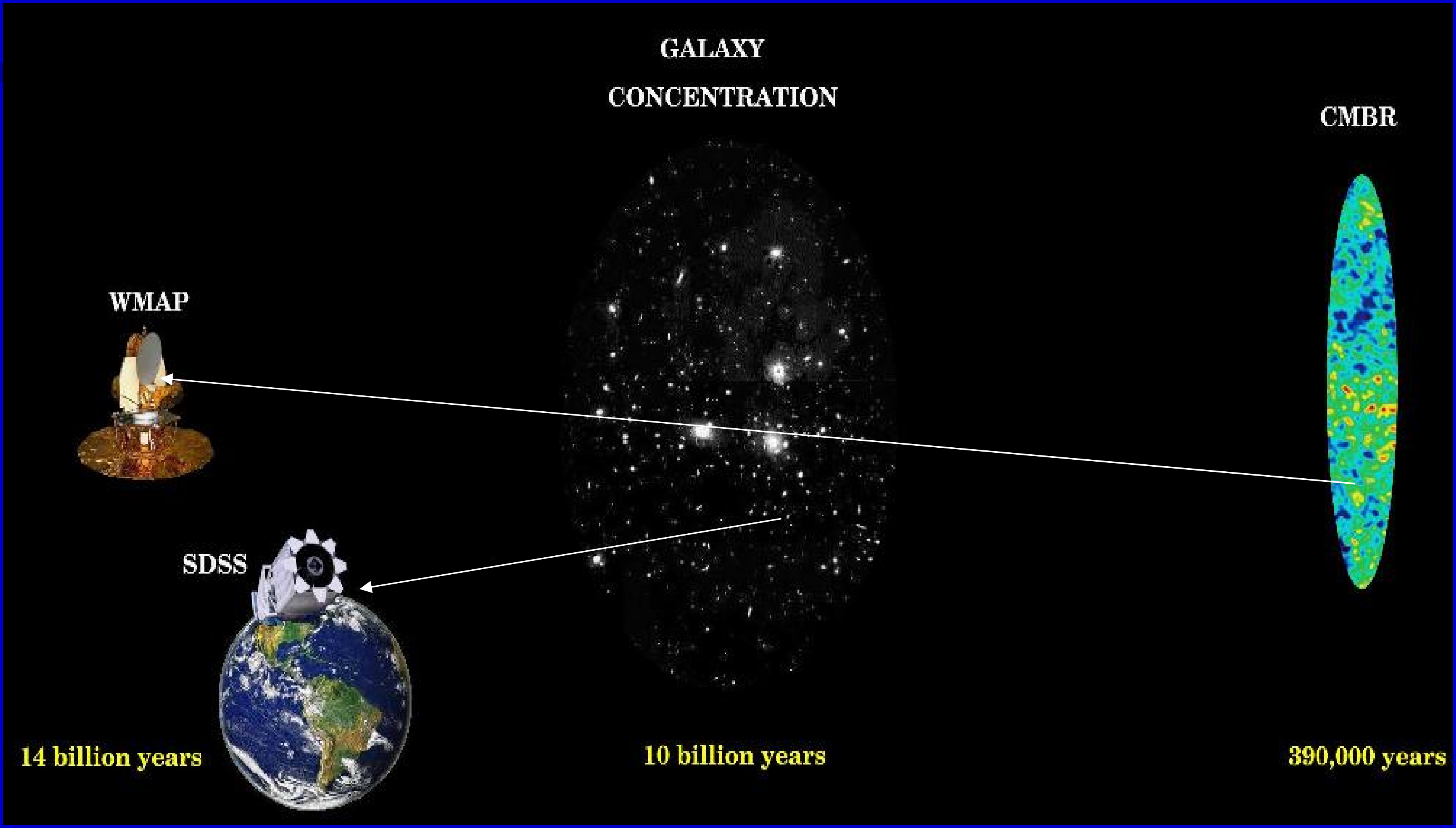
"standard" cosmological model (LCDM)
= general relativity + particle physics



LCDM fits the high-precision data

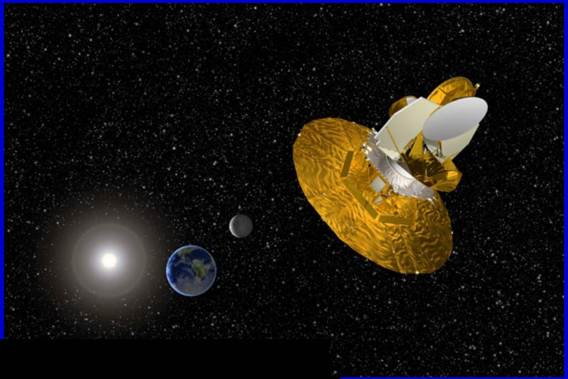


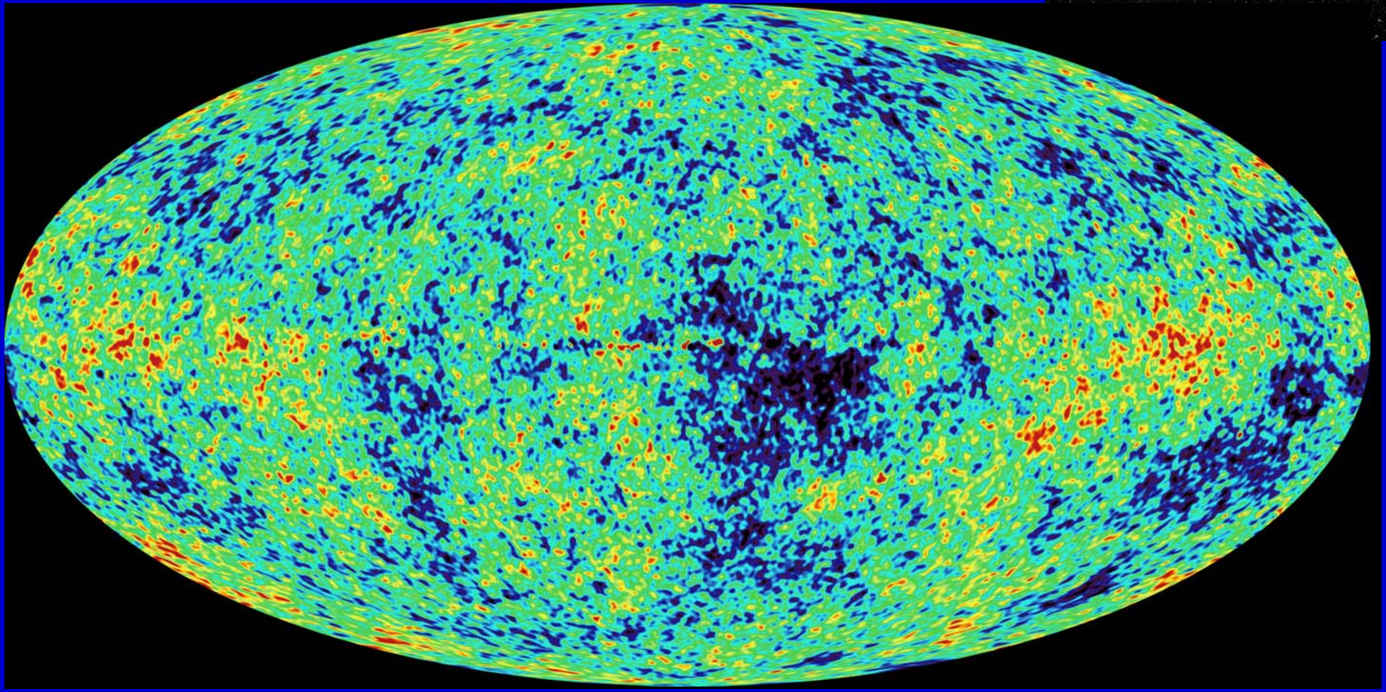
high-precision data 2001-



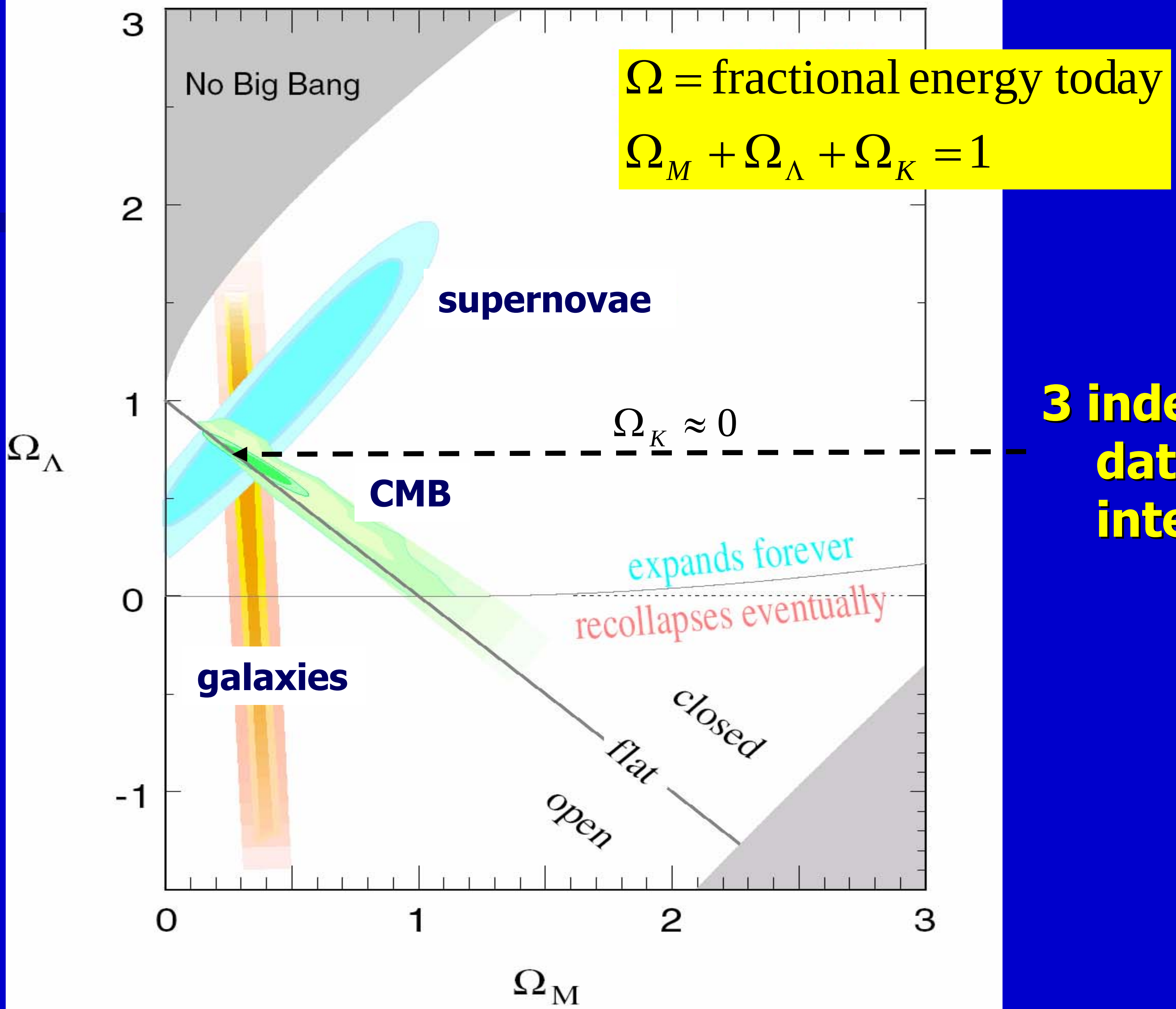
COBE launched 1990

WMAP first data 2003



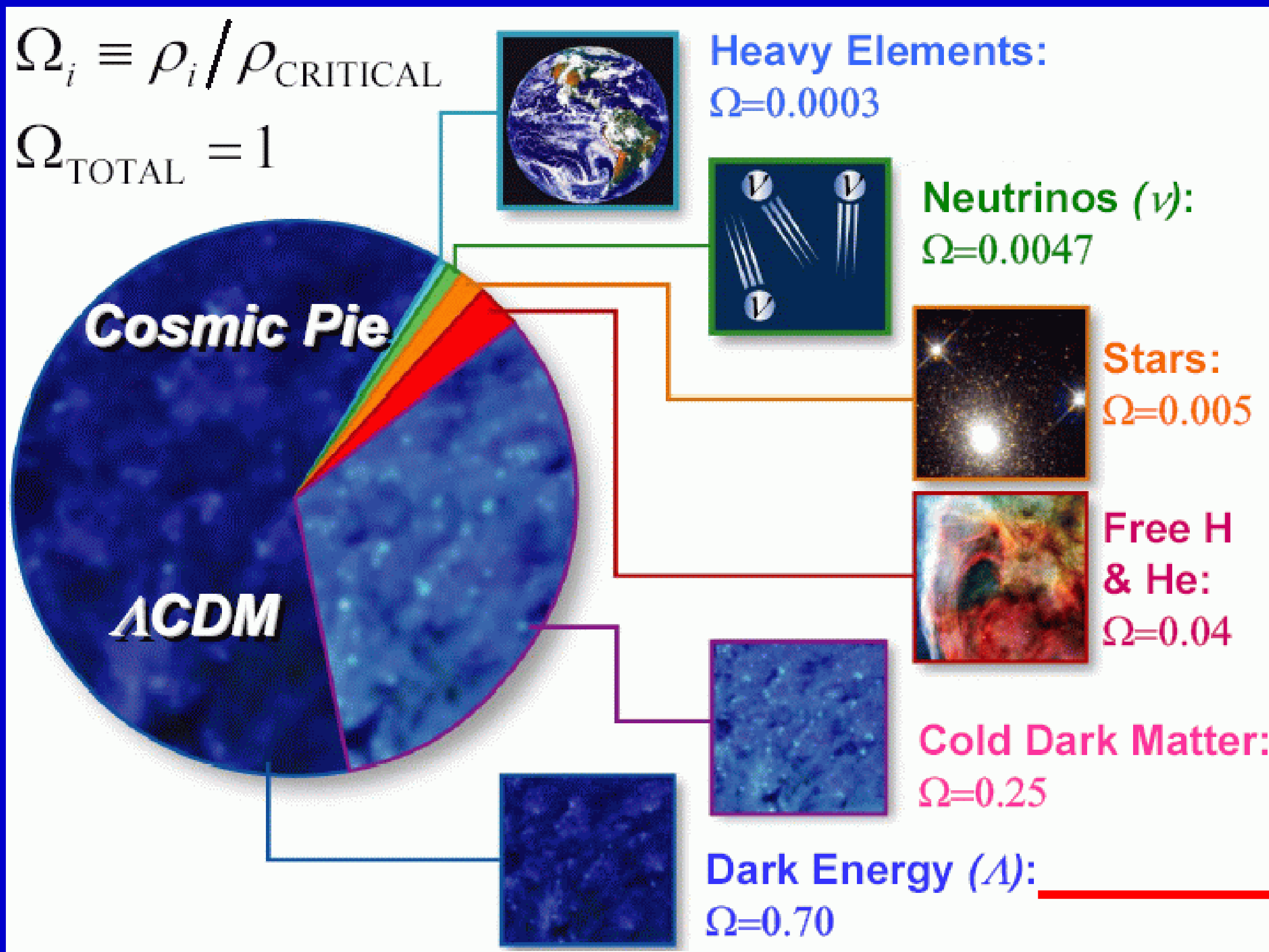


the surface of last scattering



3 independent data sets intersect

the improbable, mysterious universe



?

??

LCDM fits the data well… but we cannot explain it

- it's the simplest model
- compatible with all data up to now
- no other model gives a better statistical fit
- but …. theory cannot explain it

$$\rho_\Lambda\big|_{\text{obs}} = \frac{\Lambda}{8\pi G} \sim (10^{-3}\ \text{eV})^4$$

$$\rho_\Lambda\big|_{\text{theory}} \sim M^4_{\text{fundamental}} \geq M^4_{\text{susy}} \sim (1\,\text{TeV})^4 >> \rho_\Lambda\big|_{\text{obs}}$$

- why so small?
- and … why so fine-tuned?

$\rho_\Lambda \sim \rho_0$: crucial for structure formation

but $\rho_\Lambda \propto a^0$ while $\rho_m \propto a^{-3}$

LCDM – possible ways forward

(1) Lambda as quantum vacuum energy

$$G_{\mu\nu} = 8\pi G(T_{\mu\nu} + T_{\mu\nu}^{\mathrm{vac}}), \quad T_{\mu\nu}^{\mathrm{vac}} = -\rho_{\mathrm{vac}} g_{\mu\nu}$$

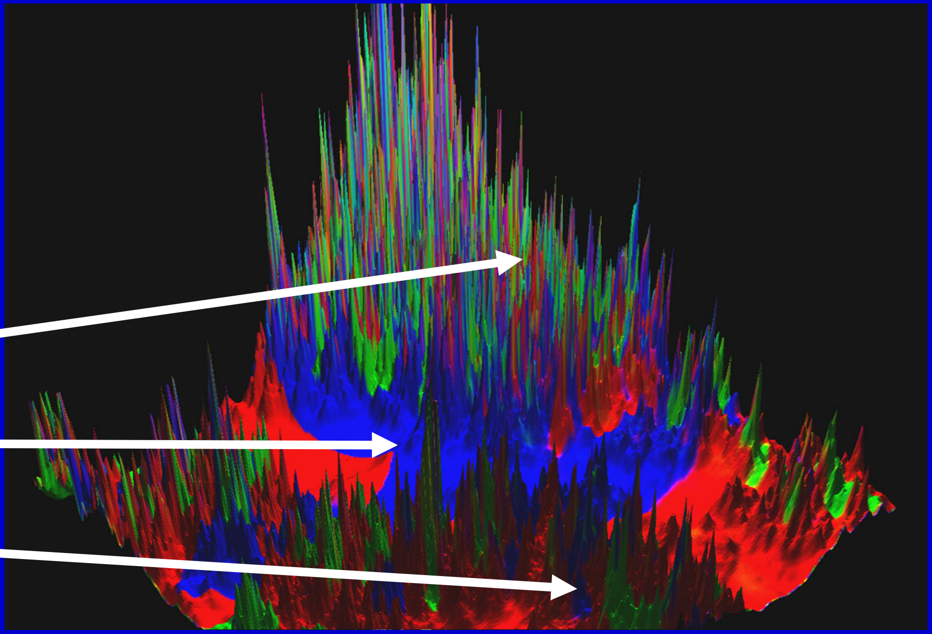
$$\rho_{\mathrm{vac}} = \frac{\Lambda}{8\pi G} \sim (10^{-3}\ \mathrm{eV})^4$$

string "landscape" and multiverse to explain fine-tuned small value?

$\rho_{\mathrm{vac}} >> \Lambda / 8\pi G$

$\rho_{\mathrm{vac}} = \Lambda / 8\pi G$

$\rho_{\mathrm{vac}} < 0$



LCDM – possible ways forward

(2) classical approach: a new gravitational constant -

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- **Λ is geometry, not vacuum energy**
- **but we *still* require fundamental quantum theory – to explain why** $\rho_{\mathrm{vac}} \equiv 0$
- **fine-tuned – but so are many other constants: eg.**

$$F_{\mathrm{strong}} \downarrow 2\% \Rightarrow \text{only H in universe}$$

$$\text{Carbon - needs He level} = 7.7\ \text{MeV (Hoyle)}$$

$$\frac{m_{\mathrm{p}}}{m_{\mathrm{e}}} = 1836 \ \text{- crucial for atoms}$$

a general, not special, fine-tuning problem

alternatives to LCDM

dynamical dark energy in GR

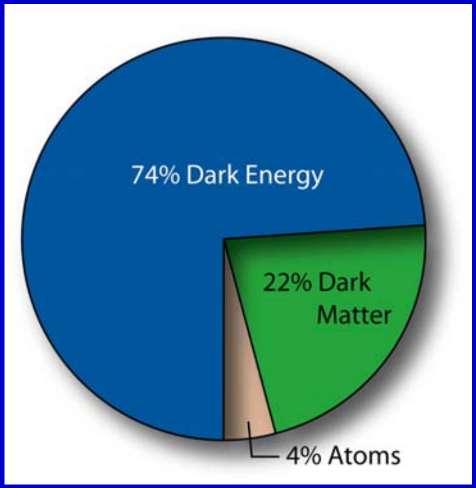
- "quintessence"
- other dynamical DE: "phantom", "k-essence", coupled DE,...
- effective 'DE' via nonlinear effects of structure formation?

dark gravity – infrared modification to GR

- 4D: scalar-tensor theories
- higher-D: braneworld models

NB – all these alternatives must *also* explain why the vacuum energy does not gravitate: $\rho_{\text{vac}} \equiv 0$

DE dynamics



$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + 8\pi G T_{\mu\nu}^{\text{dark}}$$

$$T_{\mu\nu}^{\text{dark}} = \text{time - varying DE field}$$

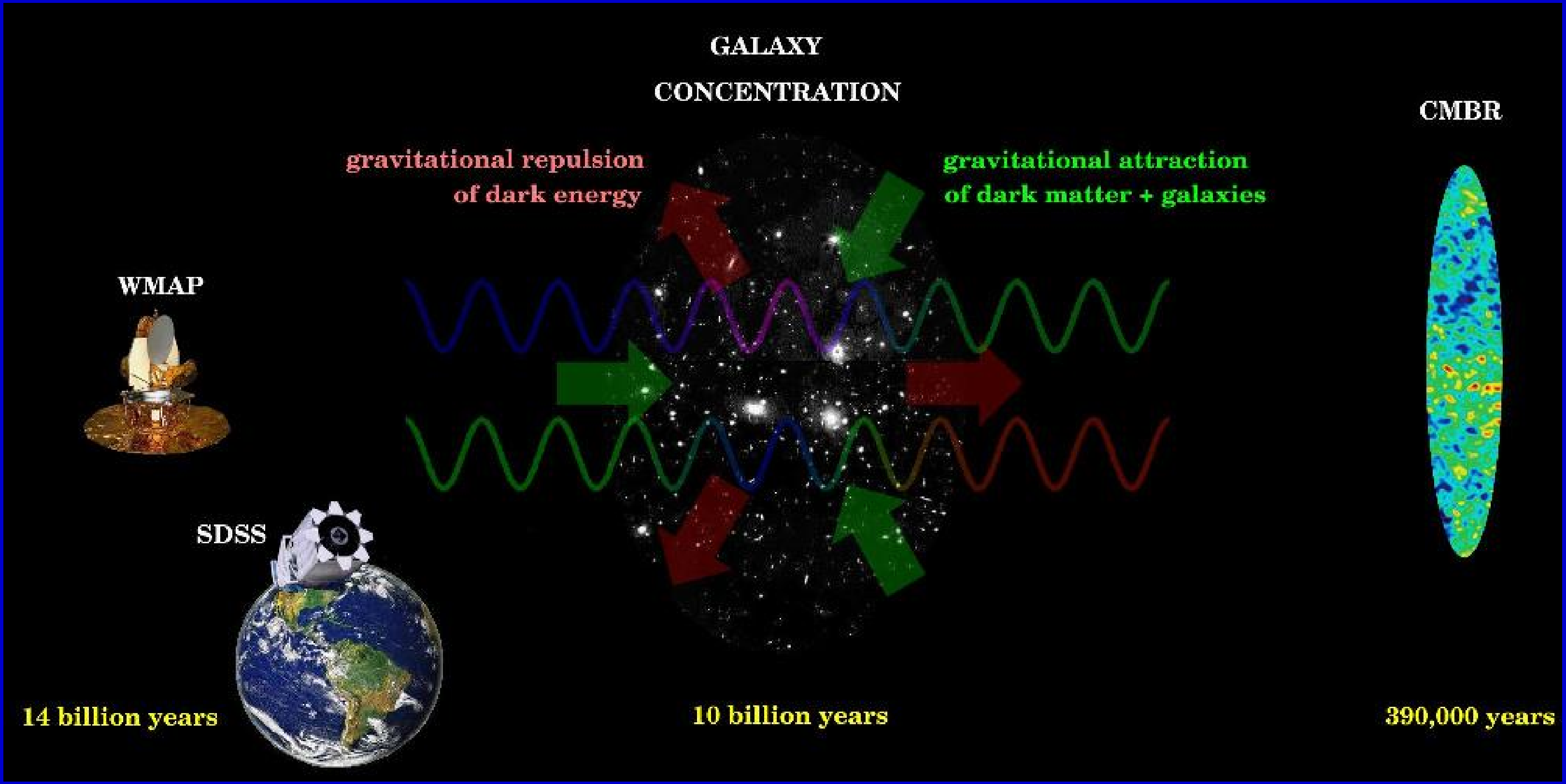
DG dynamics

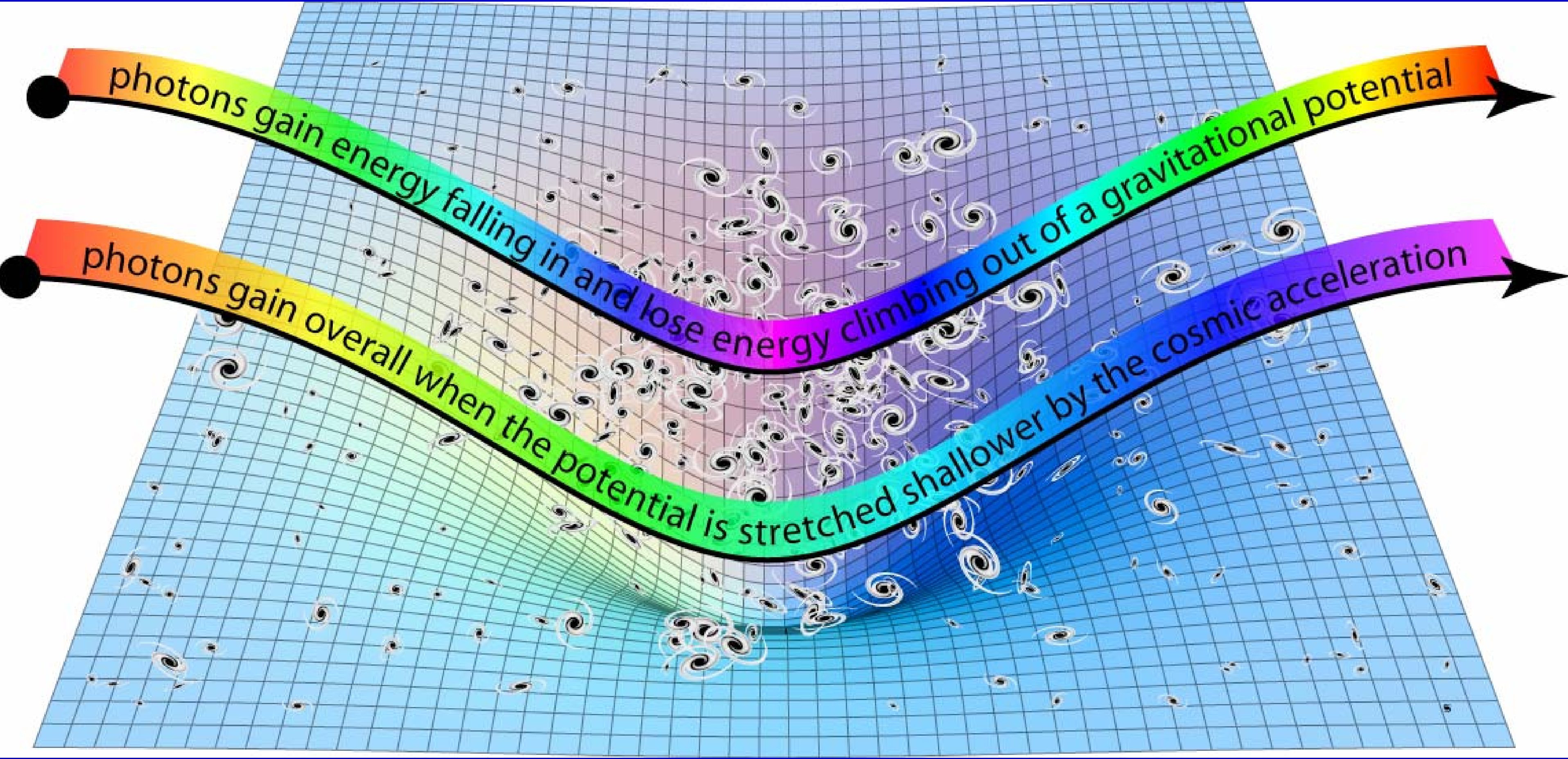
$$G_{\mu\nu} + G_{\mu\nu}^{\text{dark}} = 8\pi G T_{\mu\nu}$$

$$G_{\mu\nu}^{\text{dark}} = \text{additions to massless spin - 2 graviton}$$

observational tests of DE/DG

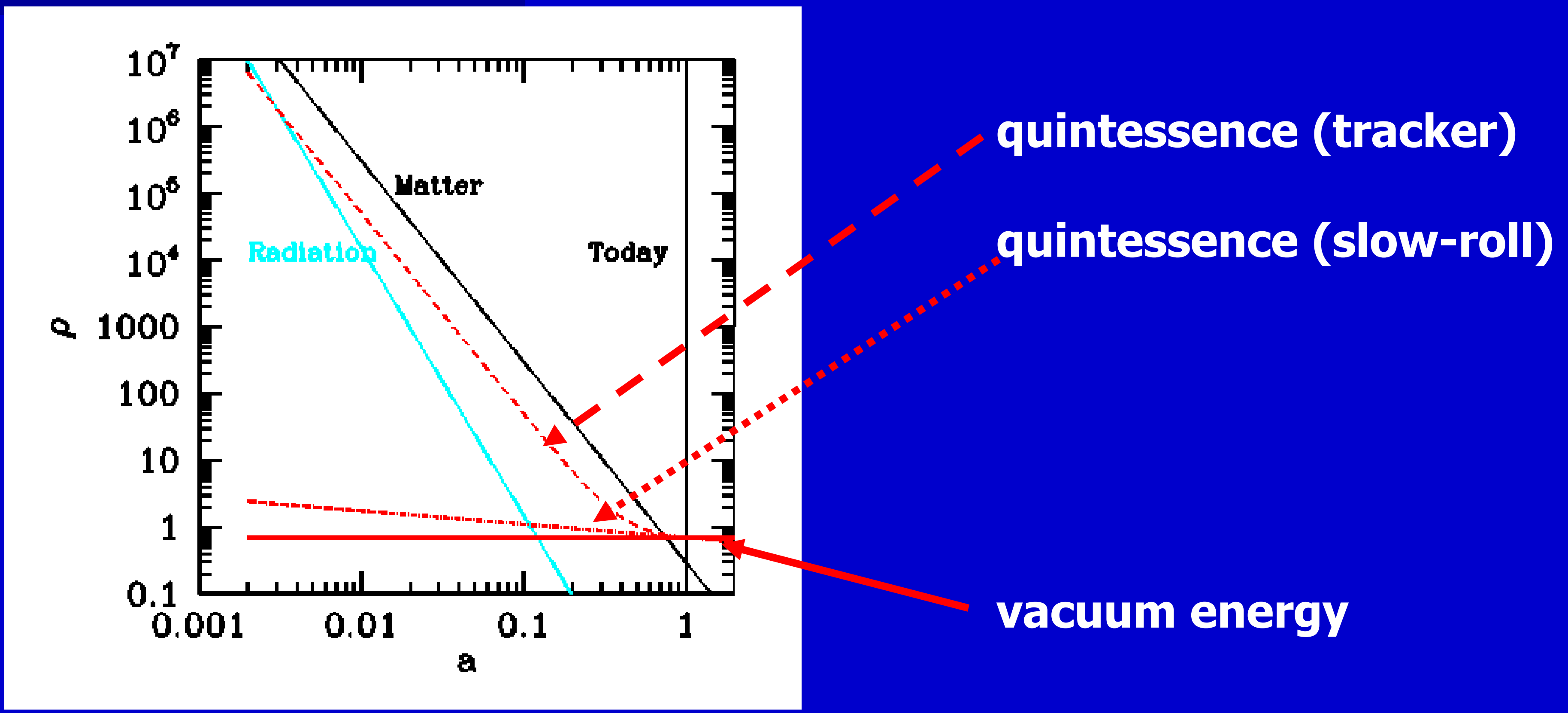
- DE and DG affect the expansion history
  test via supernova distance/redshift data
- DE and DG slow down the growth of structure
  test via CMB and galaxy distribution




photons gain energy falling in and lose energy climbing out of a gravitational potential
photons gain overall when the potential is stretched shallower by the cosmic acceleration

quintessence

motivation: solve the coincidence problem



- but need fine-tuned parameters
- SUGRA/ string theory motivation?

beyond quintessence

too many models – a signal of a theoretical crisis

can we rule out some on theoretical grounds?

$$\text{kinetic energy} \quad X = \frac{1}{2}(\vec{\nabla}\varphi)^2$$

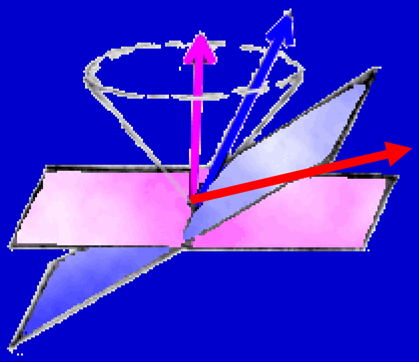
Lagrangian :

$$\text{quintessence} \quad L = -X - V(\varphi)$$

$$\text{phantom} \quad L = +X - V(\varphi)$$

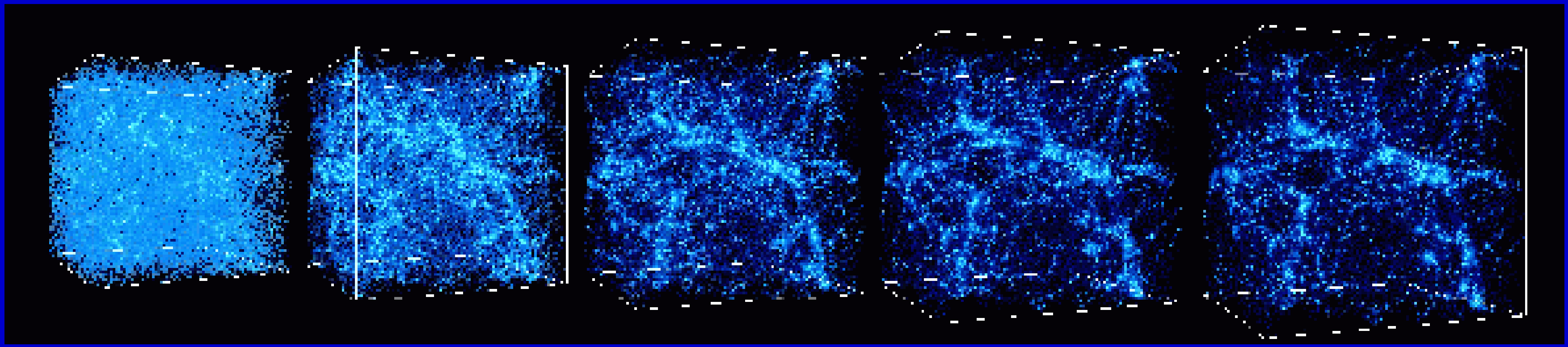
$$\text{k-essence} \quad L = F(X) - V(\varphi)$$

- **phantom – instability of the quantum vacuum**
- **k-essence – superluminal propagation of perturbations**



effective 'DE' from structure formation?

- 'best' option – if it worked!
- would solve coincidence problem – "structure formation implies acceleration"



- no exotic fields + no IR modification to GR
- but – no convincing model (and nonlinear)
  - CDM as a condensate ?
  - nonlinear back-reaction of CDM perturbations ?
  - nonlinear averaging effects ?

is dark energy a gravitational effect?

- within general relativity

  effective 'DE' from CDM inhomogeneity ?

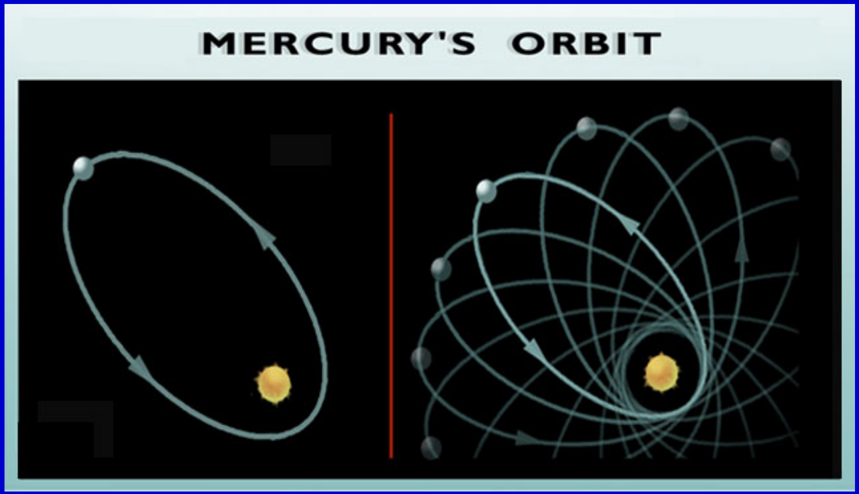
  – no model that is convincing, up to now

- modify GR? Lessons from history:

  Mercury perihelion

  – Newton + 'dark' planet ?

  no – modified gravity!



  Michelson-Morley

  – Newton + 'dark' aether ?

  no – modified dynamics

dark gravity - IR modifications to GR

$$G_{\mu\nu} + G_{\mu\nu}^{\text{dark}} = 8\pi G T_{\mu\nu}$$

$$G_{\mu\nu}^{\text{dark}} \Rightarrow \text{additions/ changes to massless spin - 2 graviton}$$

$$\rightarrow 0 \text{ on small scales/ high energies (UV)}$$

modified Friedman equation

- test via supernovae

$$H^2 + H_{\text{dark}}^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

modified structure formation

- test via CMB + galaxy distribution

key problem:

how to get cosmic acceleration at low energy without violating solar system constraints?

(solar system is also *low energy)*

4D dark gravity

scalar-tensor gravity:

$$L_{\mathrm{GR}} = R \;\rightarrow\; L = f(R) \;\text{ or }\; F(\varphi)R - (\nabla\varphi)^2 - 2U(\varphi)$$

where $R = \text{spacetime curvature scalar}$

a new spin-0 addition to the spin-2 graviton

Too many models – can we rule out some?
eg.

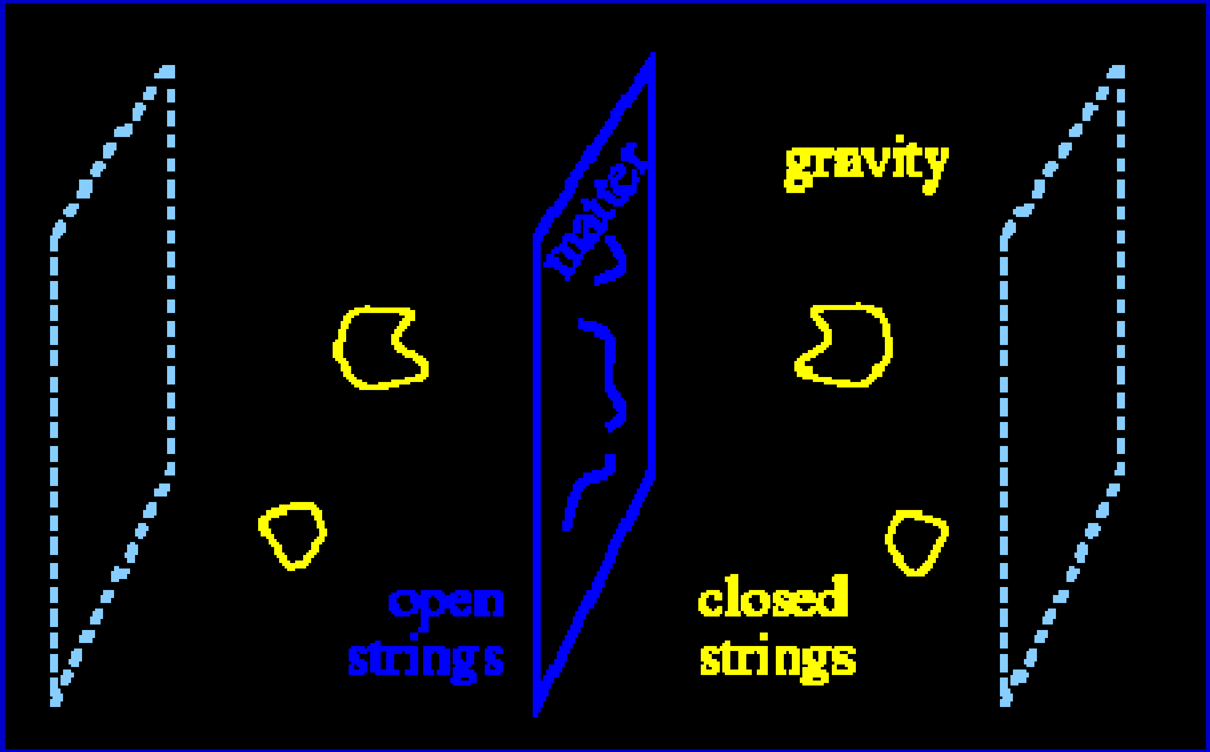
$$f(R) = R - \frac{\mu}{R}$$

at low energy,
1/*R* dominates

- **late-time acceleration**
- **passes many cosmological tests**
- **fails solar system tests**
- **also has nonlinear instabilities**

braneworld models

- our 4D universe may be moving in 10D spacetime
- motivated by string theory



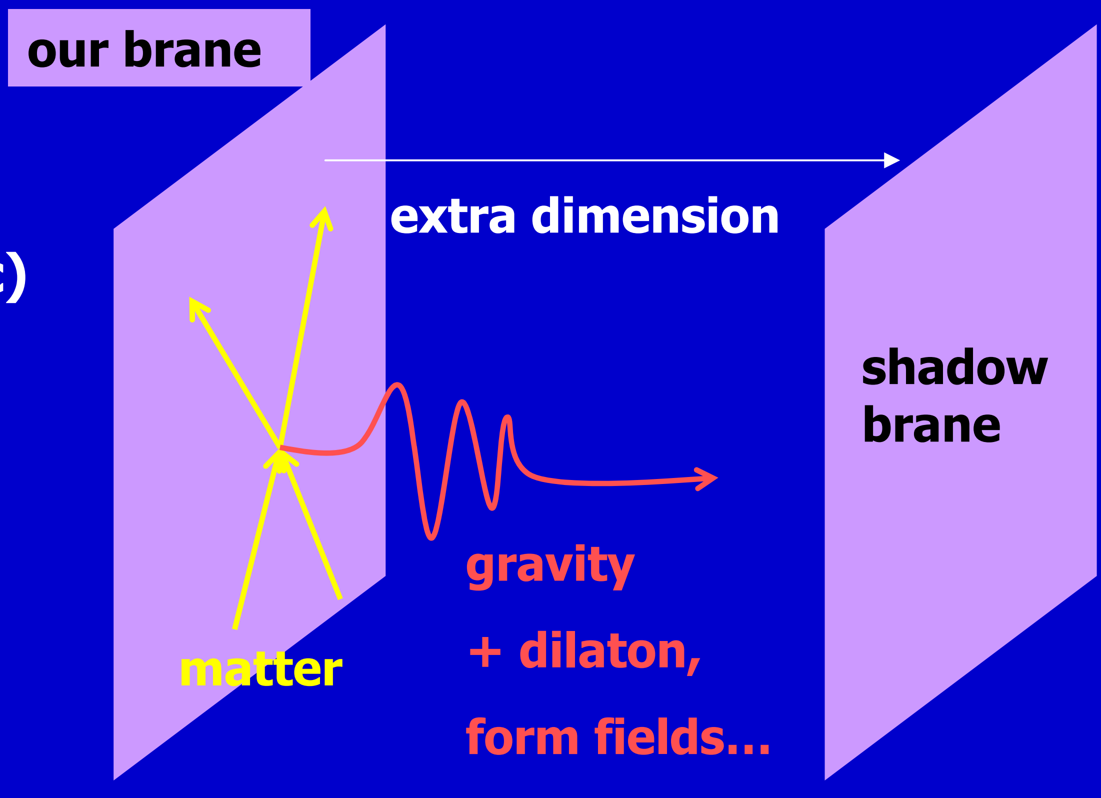
unifies the 4
interactions

dark gravity from braneworlds?

- new spin-2 massive graviton modes
- new effects from higher-D fields and other branes
- perhaps these could dominate at low energies

different possibilities

- 'bulk' fields as effective DE on the brane (eg Cyclic)
- matter on a 'shadow' brane as effective DE on the 'visible' brane
- effective 4D gravity on the brane modified in IR (eg DGP)



DGP cosmology

Friedman

$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho$$

$$\text{late time}: \quad \rho \to 0 \Rightarrow H \to \frac{1}{r_c}$$

$$\text{early time}: \quad H >> r_c^{-1} \Rightarrow H^2 \approx \frac{8\pi G}{3}\rho$$

early universe (UV) – recover GR dynamics

late universe (IR) – acceleration without DE

gravity "leaks" off the brane

therefore gravity on the brane weakens

passes the supernova test

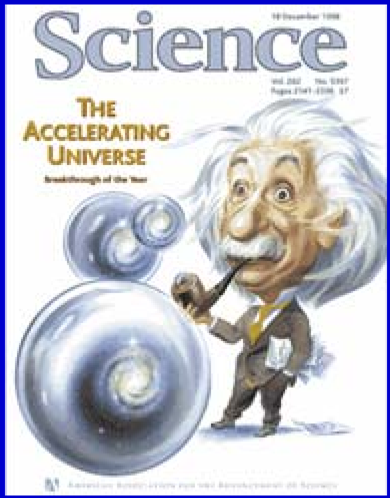
structure formation – not yet fully solved

but … has a ghost – can it be cured by UV?

conclusion - dark energy and dark gravity

- observations very strongly indicate acceleration
- simplest model LCDM cannot be explained by theory
- GR alternatives –
  very hard to get a natural model that works
- modify GR? (no dark energy) – also very hard

  e.g. even the simplest brane models



LCDM ALTERNATIVES CANNOT ESCAPE THE FUNDAMENTAL PROBLEM –
DO WE NEED A NEW PARADIGM?