# Two big puzzles in Modern Cosmology

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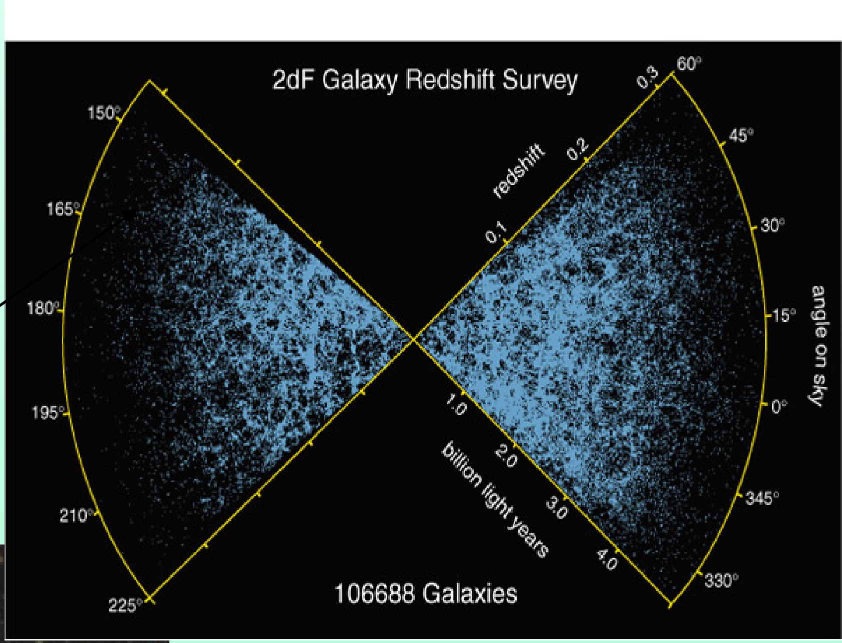
$$G^a_b + \Lambda\delta^a_b = \kappa T^a_b$$

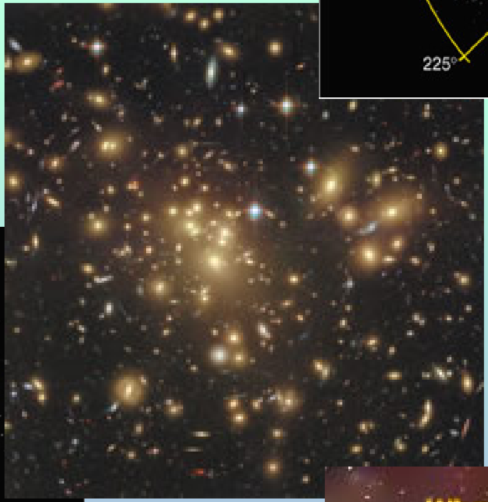
$$S_{(5)} = \frac{1}{2}M^3_{(5)}\int d^4x\, dy\sqrt{-g_{(5)}}R_{(5)} + \frac{1}{2}M^2_{(4)}\int d^4x\sqrt{-g_{(4)}}R_{(4)} + S_{matter}$$

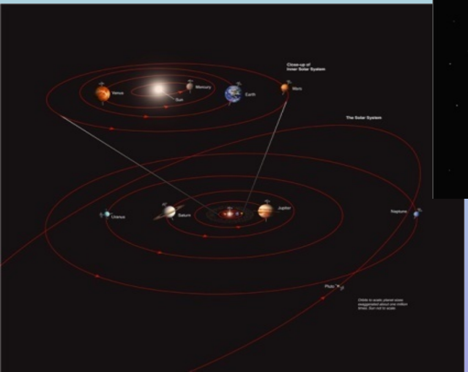
$$P_\kappa(l) = \frac{9}{4}H_o^4\Omega_m^2\int_0^{\chi_H}\frac{g^2(\chi)}{a^2(\chi)}P_{3D}\left(l/\sin_K(\chi),\chi\right)d\chi$$

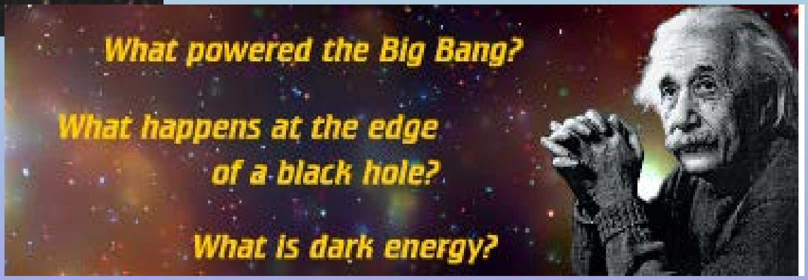
# What is cosmology?

Cosmology is the science that studies the physics and astrophysics of the universe as a whole and also phenomena at very large distances in the universe





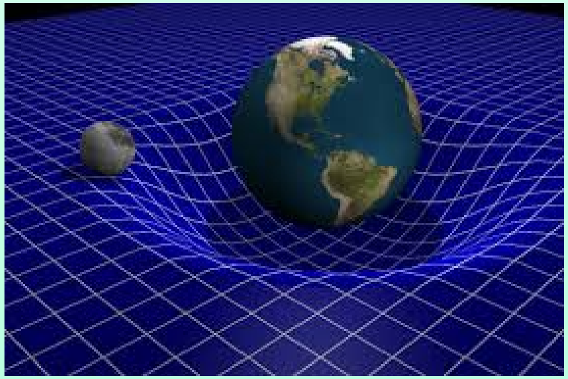
# The standard model used in cosmology is called the Friedmann-Lemaitre-Robertson-Walker (FLRW) model

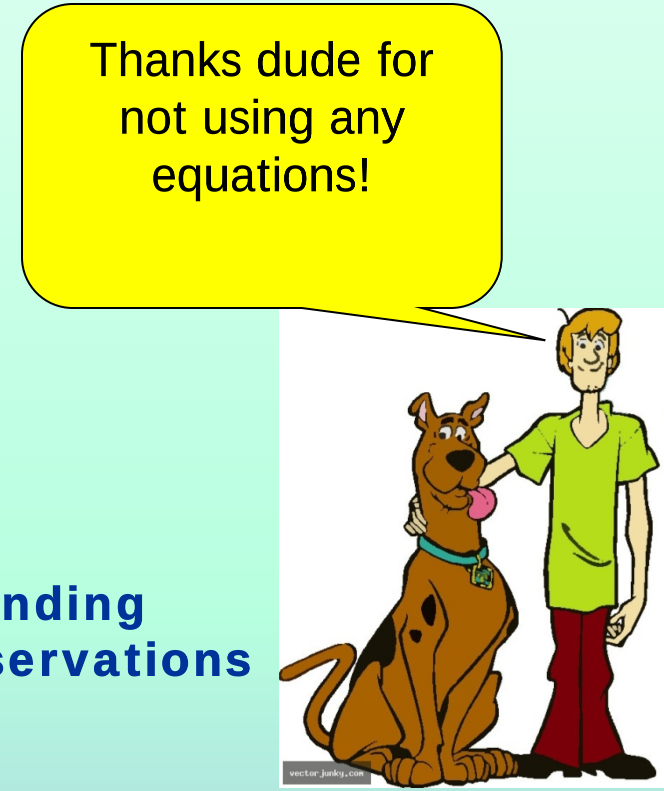
**The model is based on General Relativity,**
**the theory of gravity of Einstein.**

**The model combines:**
**The Big Bang ideas of Friedmann and Lemaitre**
**to**
**The geometrical model of Robertson and Walker**

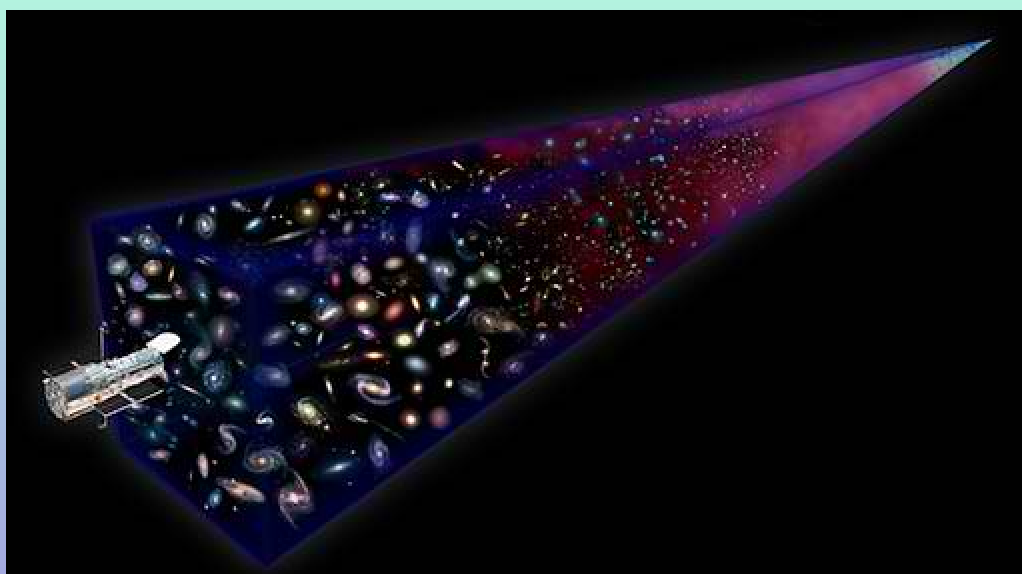
*From left: Aleksandr Aleksandrovich **Friedmann** (photo AIP Emilio Segre Visual Archives); Monsignor Georges **Lemaître**, priest and scientist (photo source Wikipedia); Howard Percy **Robertson** (photo AIP Emilio Segre Visual Archives); Arthur **Walker** (photo source virgo.physics.ucdavis.edu)*

## Einstein and Friedmann equations link the geometry of the universe to its matter and energy content

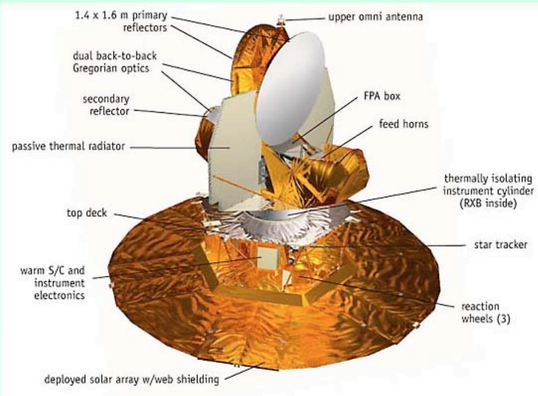


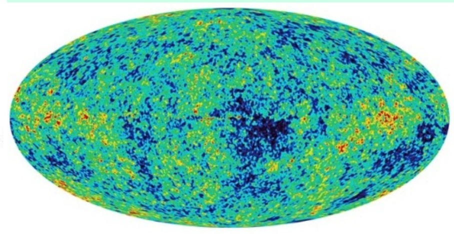



## The equations obtained describe an expanding universe in agreement with astronomical observations

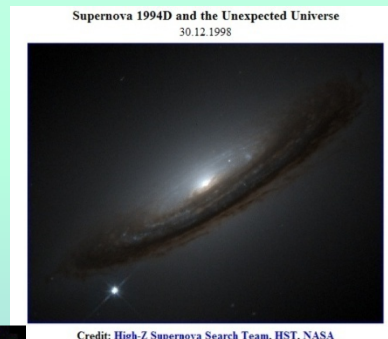


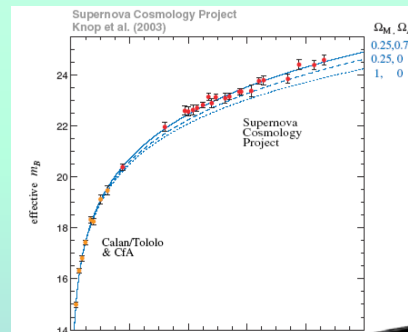
# Great times for Cosmology with a plethora of complementary astronomical data



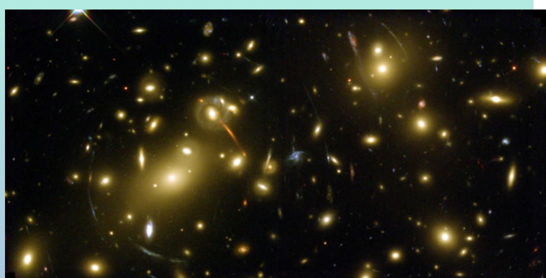



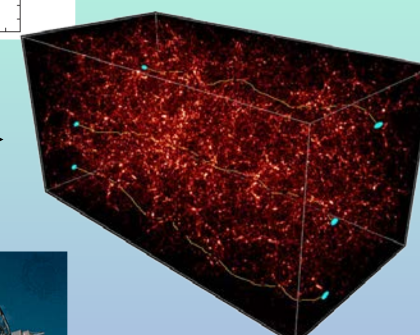
Cosmic Microwave Background (CMB)
a relic radiation from the Big-Bang.
Discovered after a nice history.



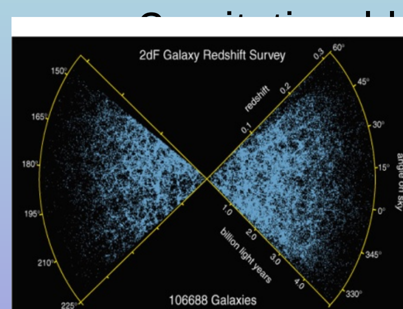



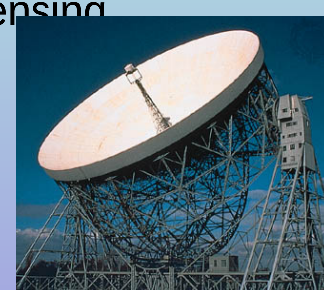

- Distance measurements to Supernovae





- Gravitational lensing



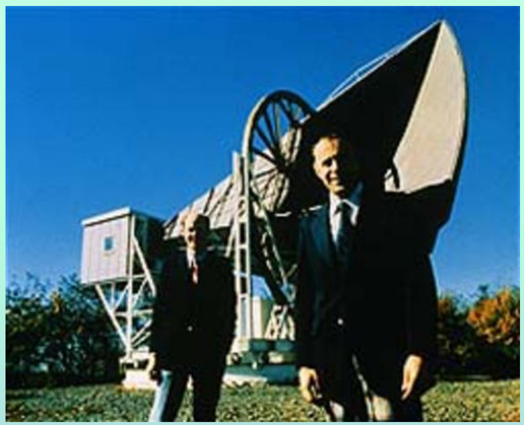



- Large scale structure measurements and surveys

# The Cosmic Microwave Background Radiation discovery as a pillar of the Big Bang standard model of Modern Cosmology

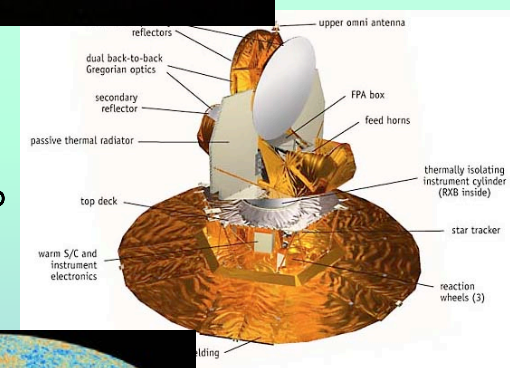
Gamov predicted the signal in 1945, 1948

Discovered by accident by Penzias and Wilson at Bell Labs (NJ) in 1964.
Received the **Nobel Prize 1978**

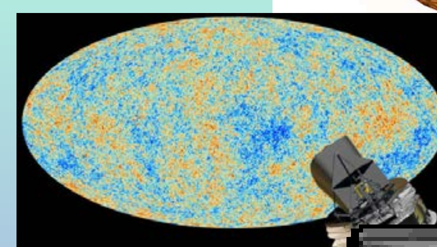


Dicke and Peebles at Princeton University, 1965

NASA COBE satellite




NASA WMAP satellite



ESA PLANCK satellite

CMB observation at home

# Remarkable progress was achieved during the last 100 years using the standard model of cosmology

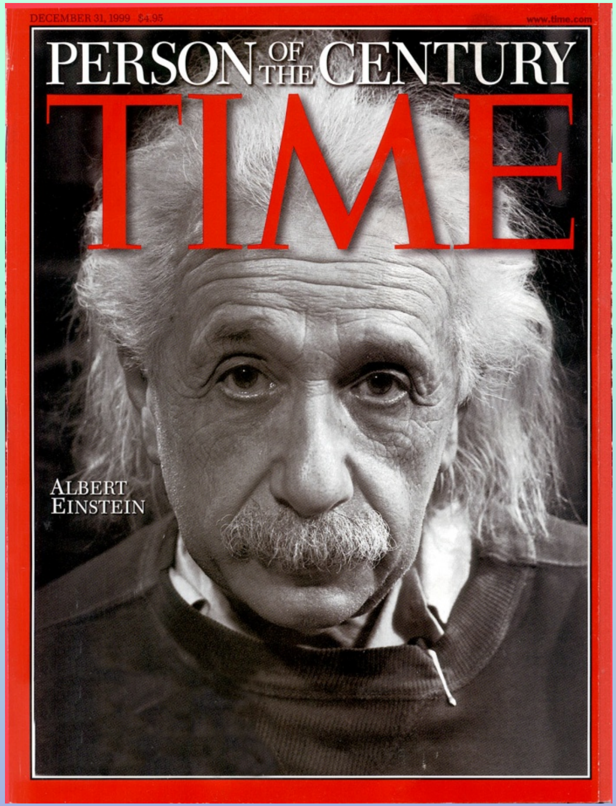
- Discovery and precision measurements of the expansion of the universe

- Discovery and precision measurements of the cosmic microwave background (CMB) radiation, a fossil radiations from very early stages of the universe

- A coherent history of structure formations in the universe

- Determination of the age of universe of about 13.7 billions years

- Concordance of results from independent cosmological data sets:
  - distances to supernovae
  - CMB
  - gravitational lensing
  - Baryon acoustic oscillations
  - galaxy clustering
  - galaxy cluster counts
  - ...



# But 2 remarkable puzzles have also been encountered and confirmed

## Puzzle One: Dark Matter

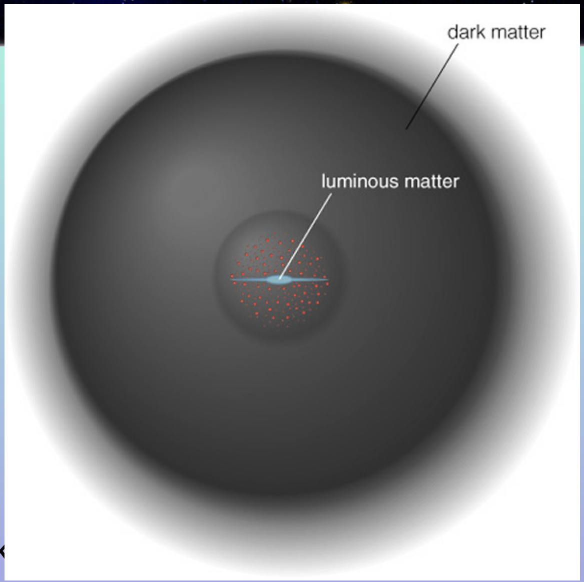
present in galaxies and clusters of galaxies in the universe

We can’t see it, we can’t bump into it

~80-90% or more of the attractive gravitating matter in the universe

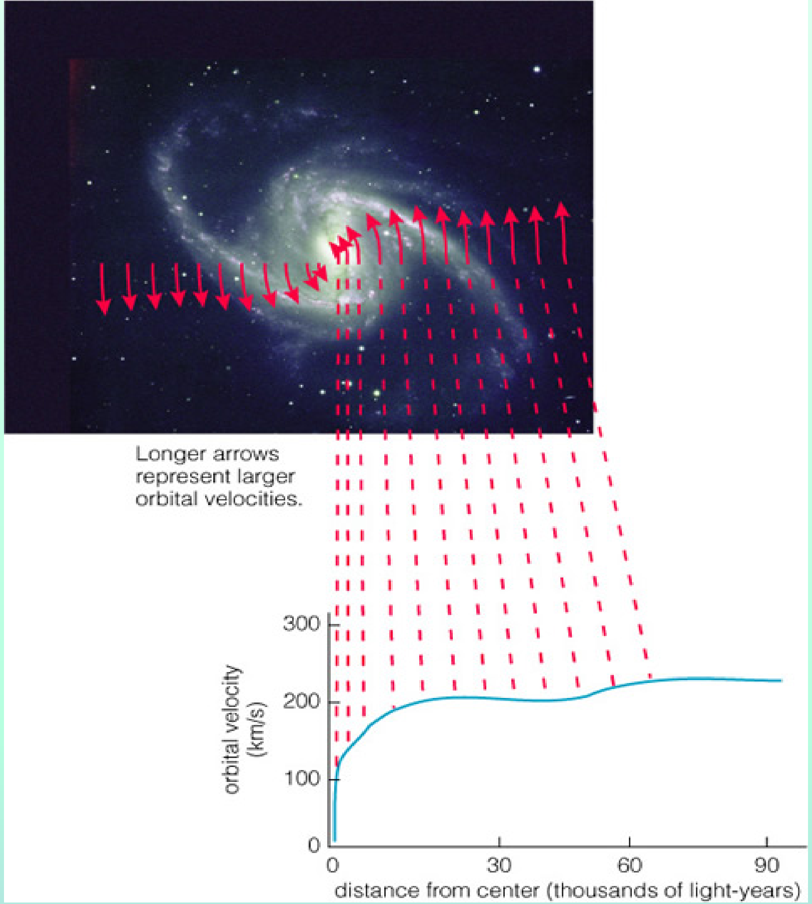
does NOT emit or absorb any type of electromagnetic radiation

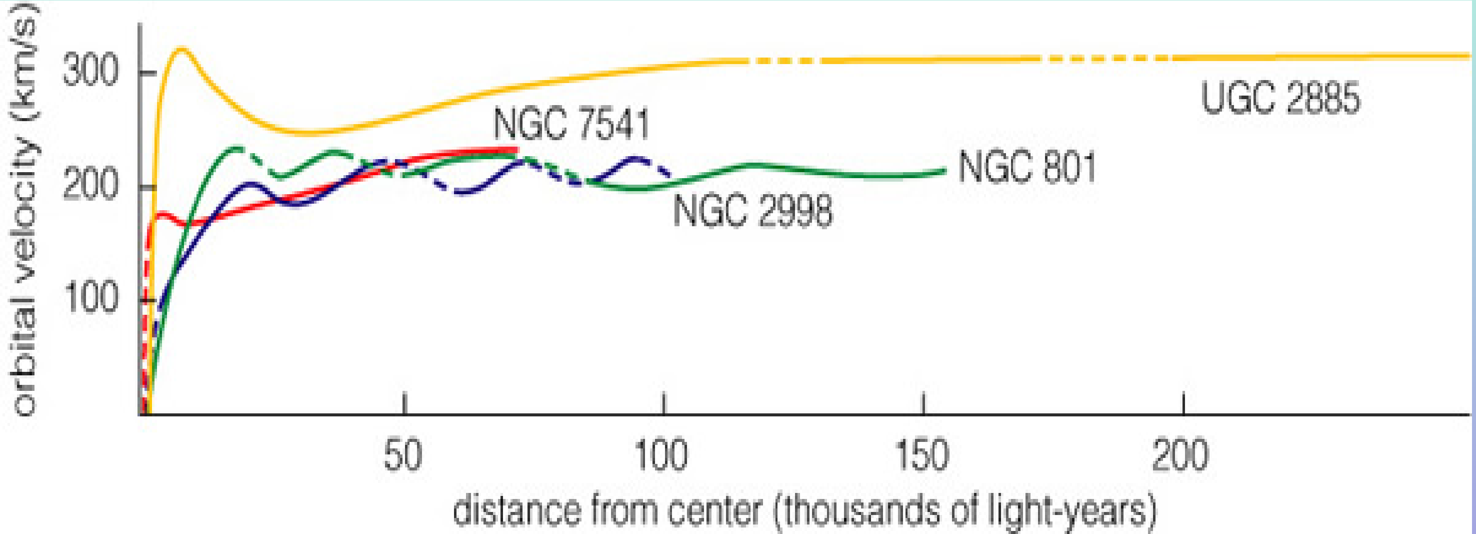
Does not interact with ordinary baryonic matter except by gravity



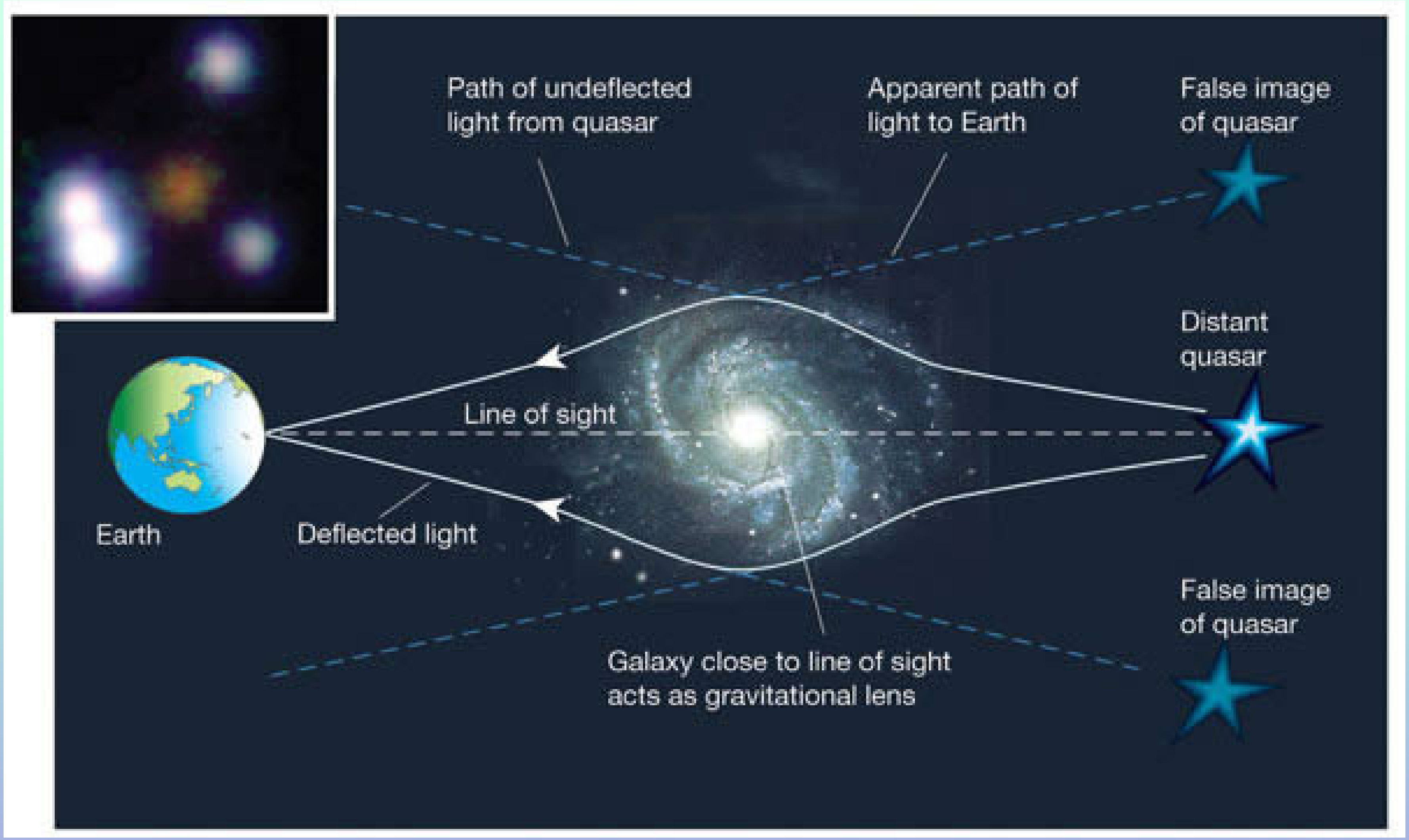
# Evidence-1 for Dark Matter: From rotation curves of galaxies

- **Gravity force in galaxies is much larger than expected**
- **As a result the rotation curves remain flat (horizontal)**
- **This indicate a mass ~5 times larger than expected from ordinary matter**



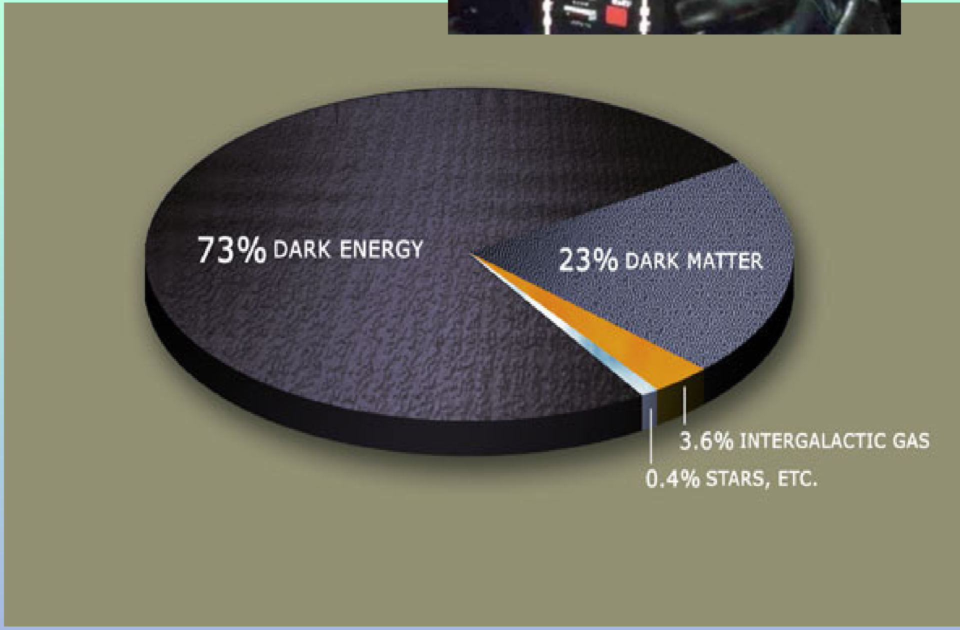



## Evidence-2: the light-deflection angle caused by a galaxy also indicates a mass of the galaxy that is ~5 times larger then what is expected from ordinary matter



## Puzzle Two:
## Cosmic acceleration and Dark Energy

- The expansion of the universe is speeding up
- One would expect the expansion to be slowing down
- Complementary astronomical observations have been indicating this for 17 years (1998-2015)



# The discovery of cosmic acceleration, the story, and the Nobel Prize

The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

- **The Nobel Prize in Physics 2011**
- Nobel Prize Award Ceremony
- Saul Perlmutter
- Brian P. Schmidt
- Adam G. Riess

Photo: U. Montan

Saul Perlmutter

Photo: U. Montan

Brian P. Schmidt

Photo: U. Montan

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

# A big challenge to physics and science

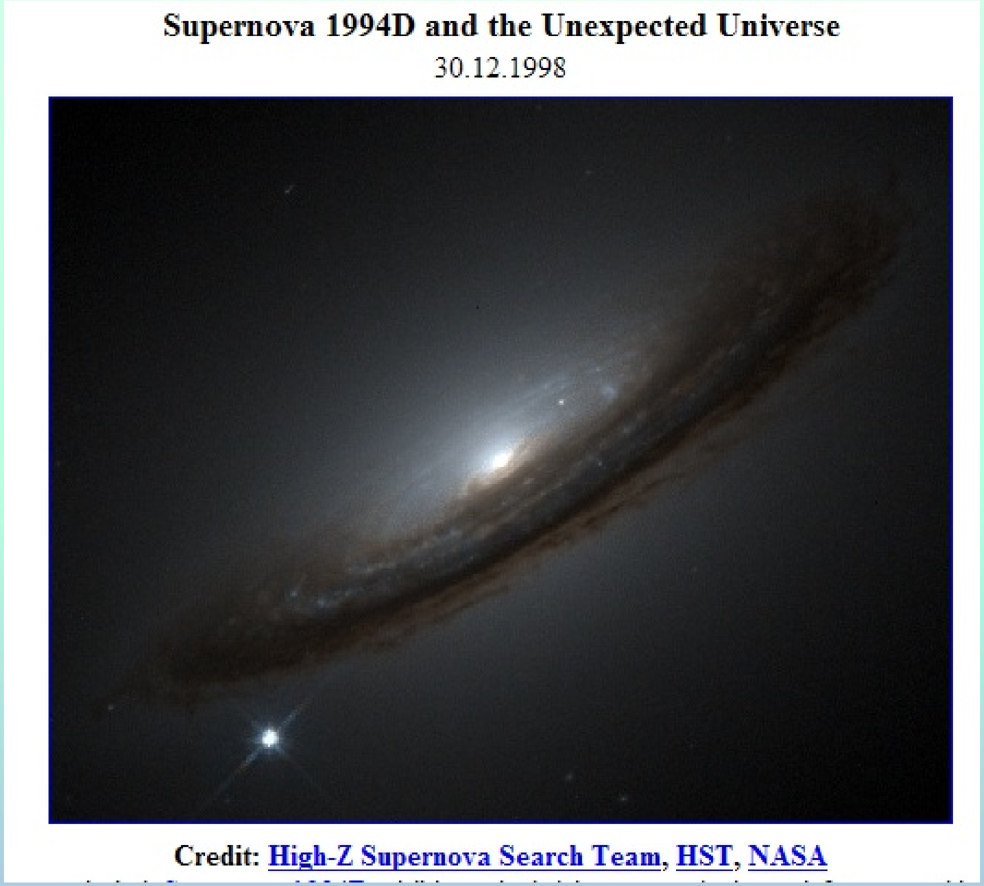

- Cosmic expansion is well understood but the acceleration of this expansion is not!

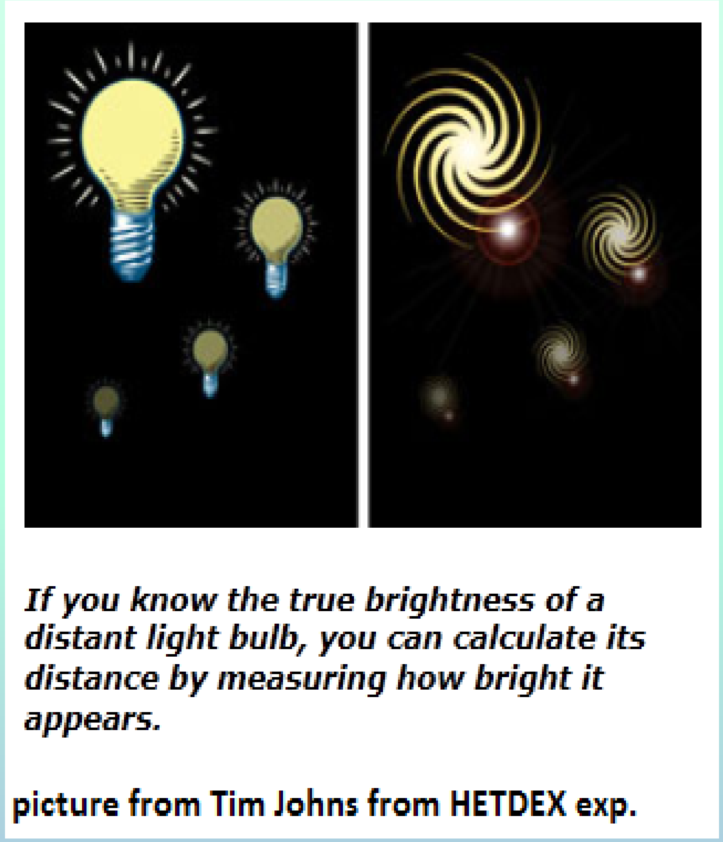
  (for example, see: Ishak, Upadhye, and Spergel, PRD 2006; Dossett & Ishak, PRD 2011, 2012, 2013)

- This problem is linked to other fields of physics beside cosmology

  (for example, see: Upadhye, Ishak, Steinhardt, PRD 2005; Ishak Found. Physics J. 2007; Ishak & Moldenhauer, JCAP, 2009)

# Evidence for cosmic acceleration from Supernovae (SN) Type Ia observations (since 1998)



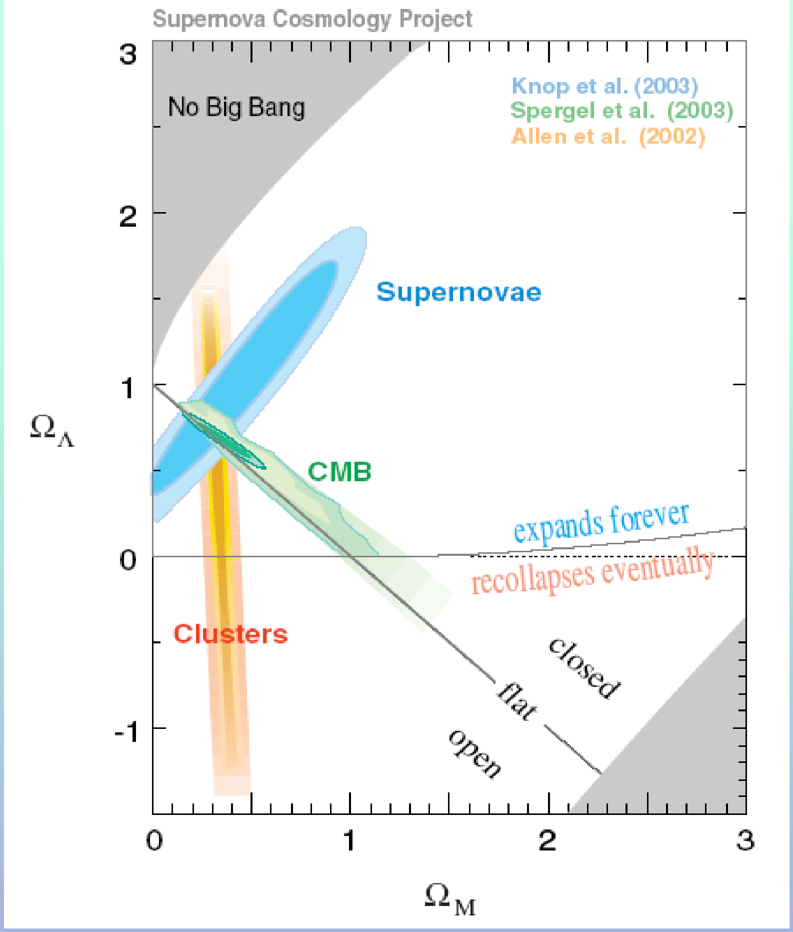



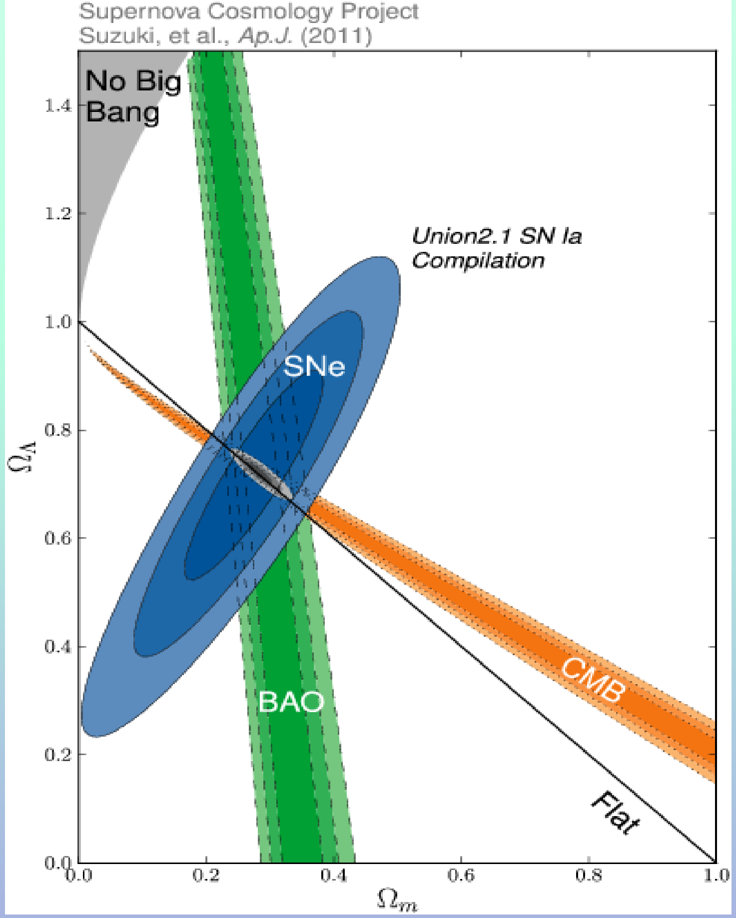

Astronomers have identified several hundreds of supernovae for this purpose.

Each supernova appear dimmer and further than expected without acceleration.


# Several Independent observations all agree on the same result:

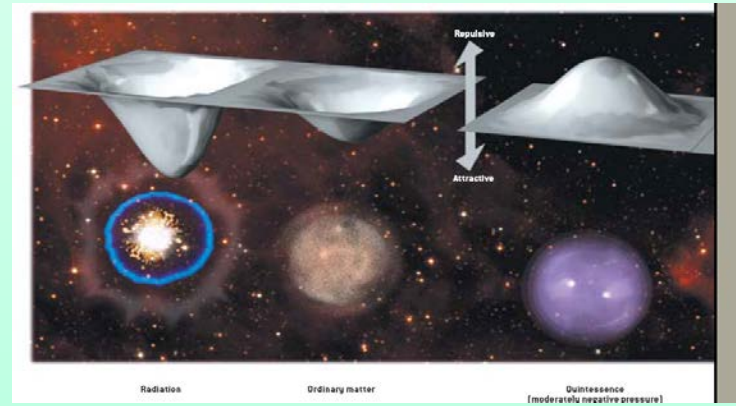
# The parameter $\Omega_\Lambda$ is not zero and that implies a cosmic acceleration

# Why is the expansion of the universe accelerating?

- Proposed possibilities in thousands of scientific publications:

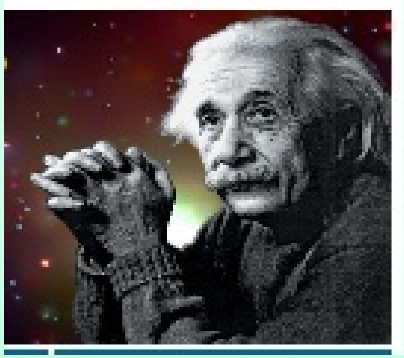



I. A dark energy component in the universe
  - Vacuum energy (recall QFT, Casimir plates)
  - A quintessence scalar field (for example, see: Upadhye, Ishak, Steinhardt, PRD 2005; Ishak, MNRAS, 2005).

II. A simple geometrical cosmological constant of nature, but this is not satisfactory for all fields of physics. (for example, see: Ishak, Found. Phys. J. 2007)


III. A modification to General Relativity at cosmological scales: e.g. higher order gravity models or higher dimensional physics (DGP models)
(for example, see: Dossett & Ishak, PRD, 2012; Ishak & Moldenhauer, JCAP, 2009)

IV. An apparent acceleration due to an uneven expansion rate in an inhomogeneous cosmological model (see for example Ishak, Peel, Troxel, PRL 2013)

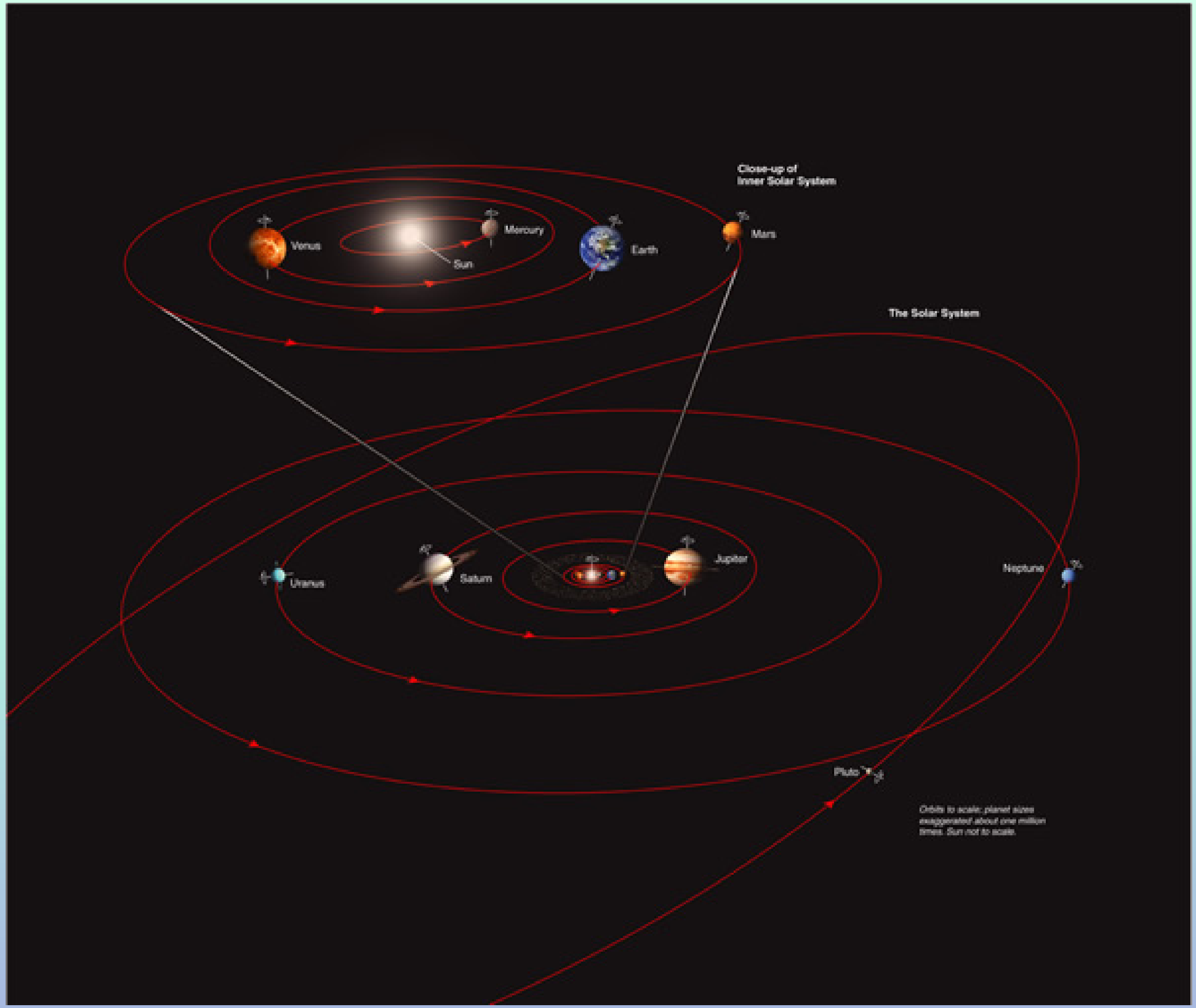


# Conclusions

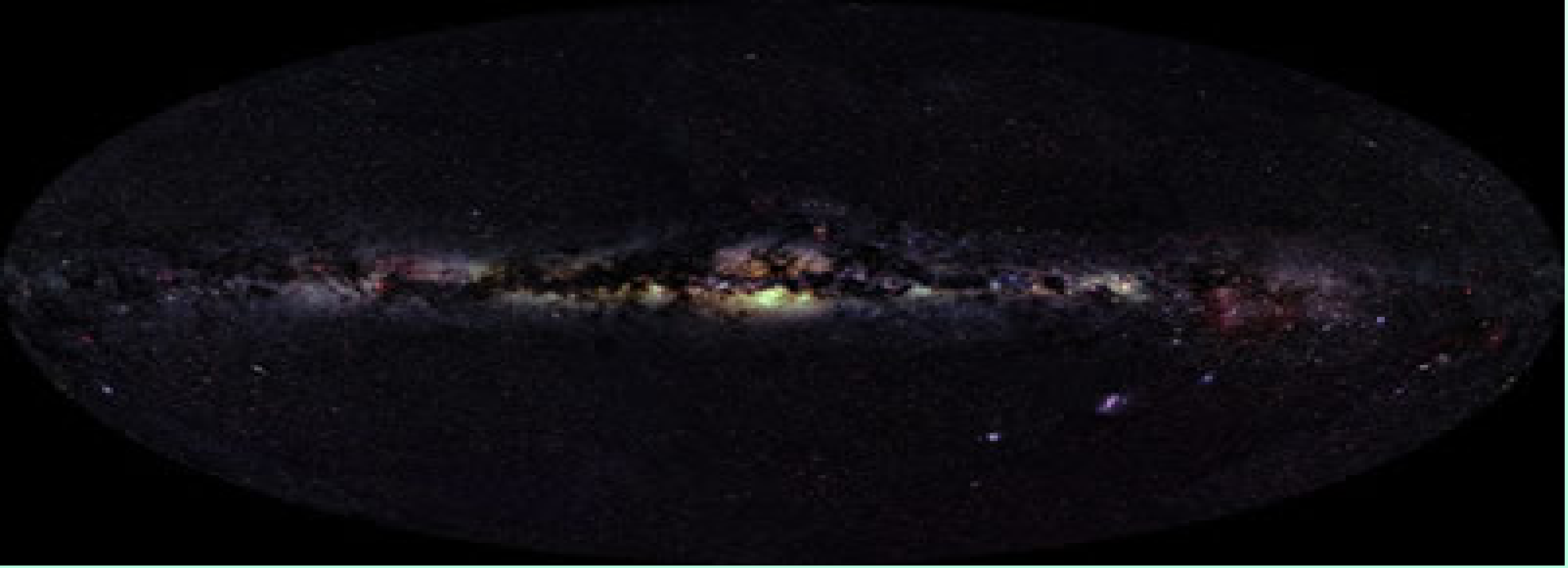
- We learned a lot about our universe as a whole (model, expansion, age, ...).
- There is a great concordance between different and independent cosmological observations that led to a concordance standard cosmological model.
- There are now two big puzzles: dark matter and cosmic acceleration (dark energy)
- Cosmology is booming with new data and that should help to solve some these outstanding questions.

Work in progress

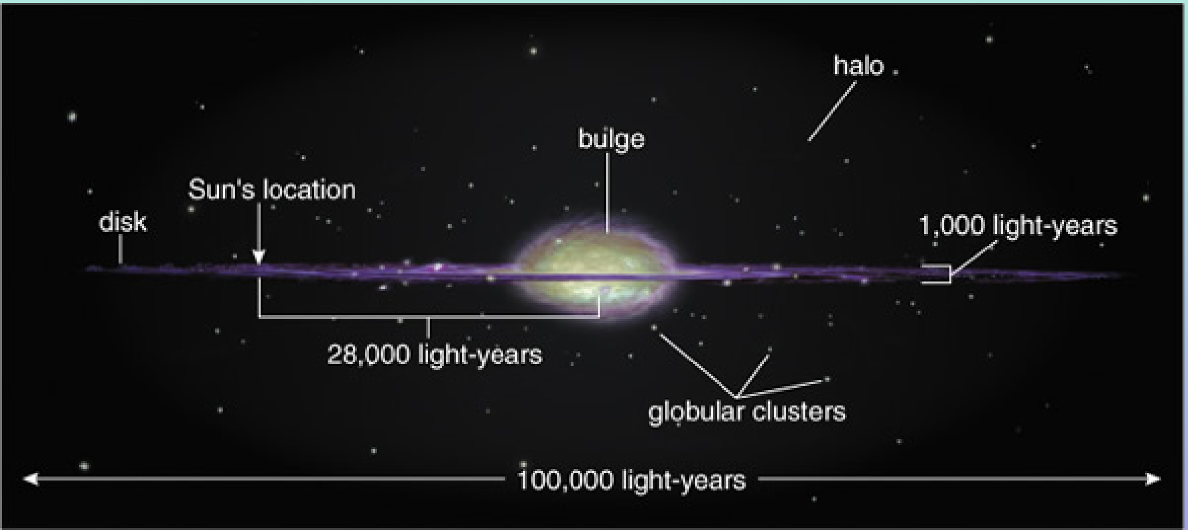
# Our solar system

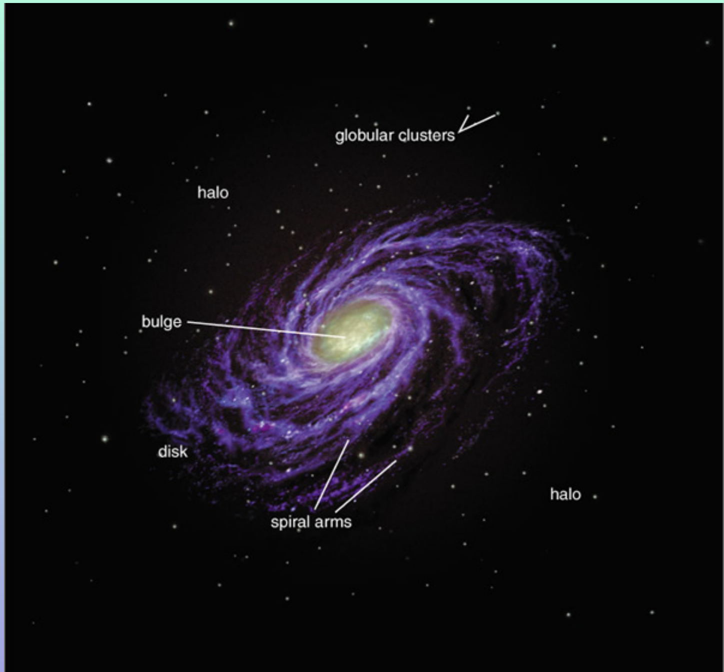



## The Sun is a typical star.

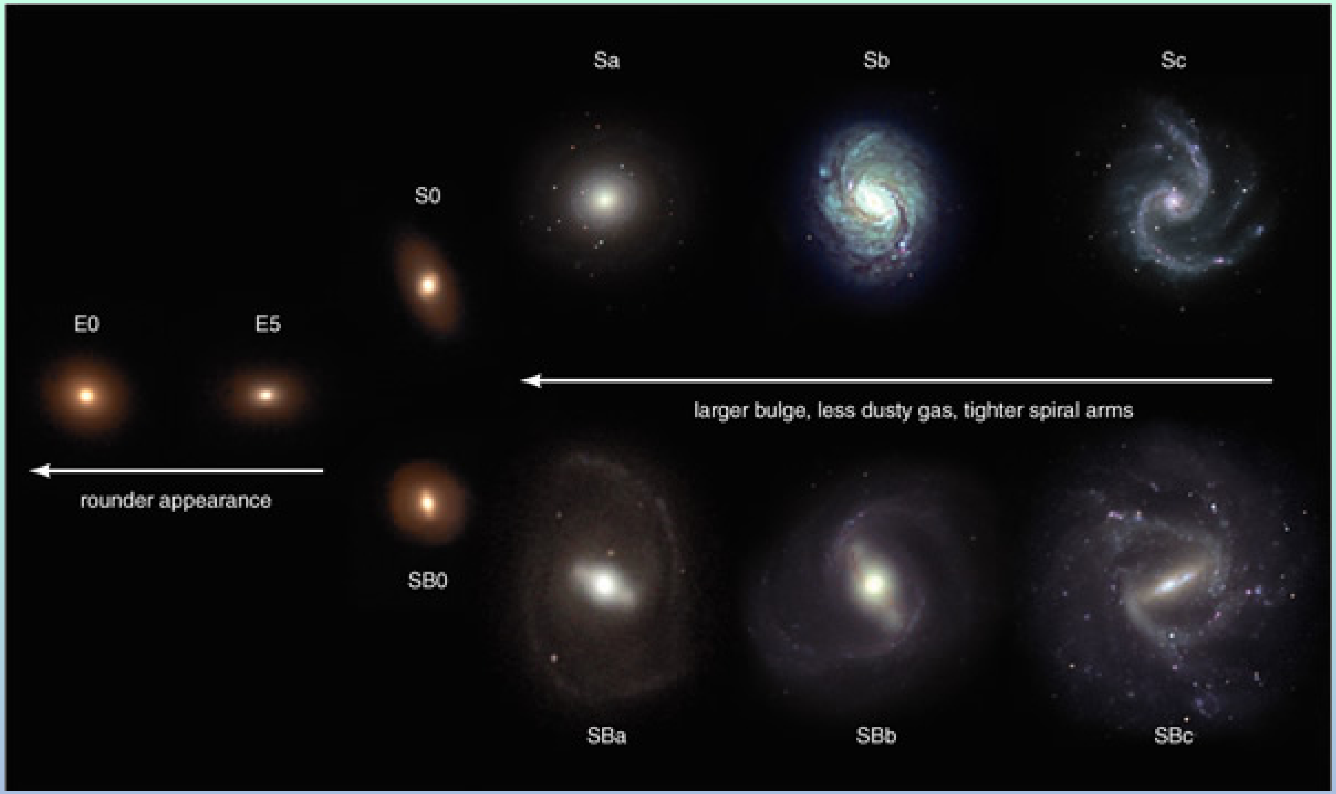


# Our galaxy: called the Milky Way is home to 100 billion stars like the sun



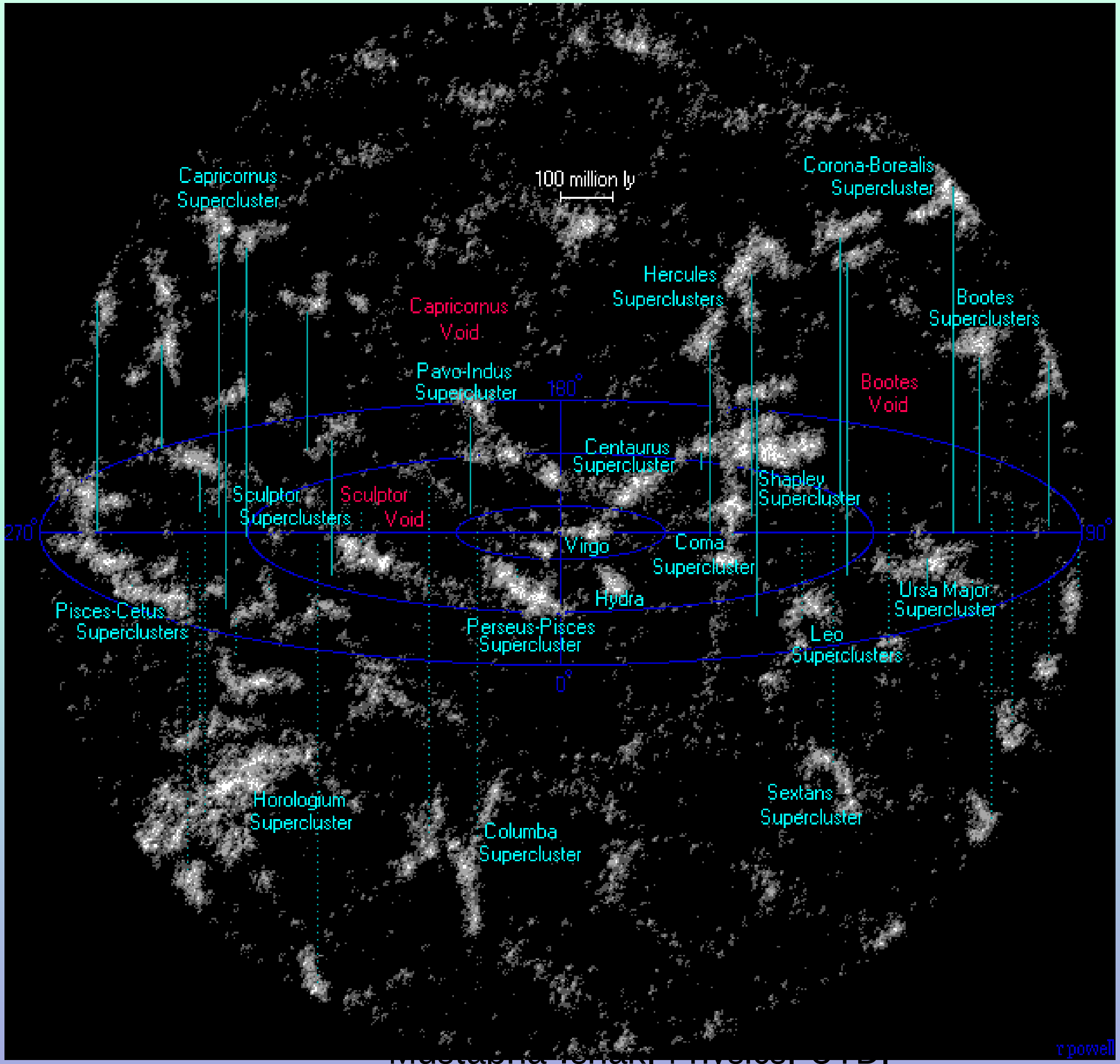



# There are several billions of galaxies of various types in the observable universe

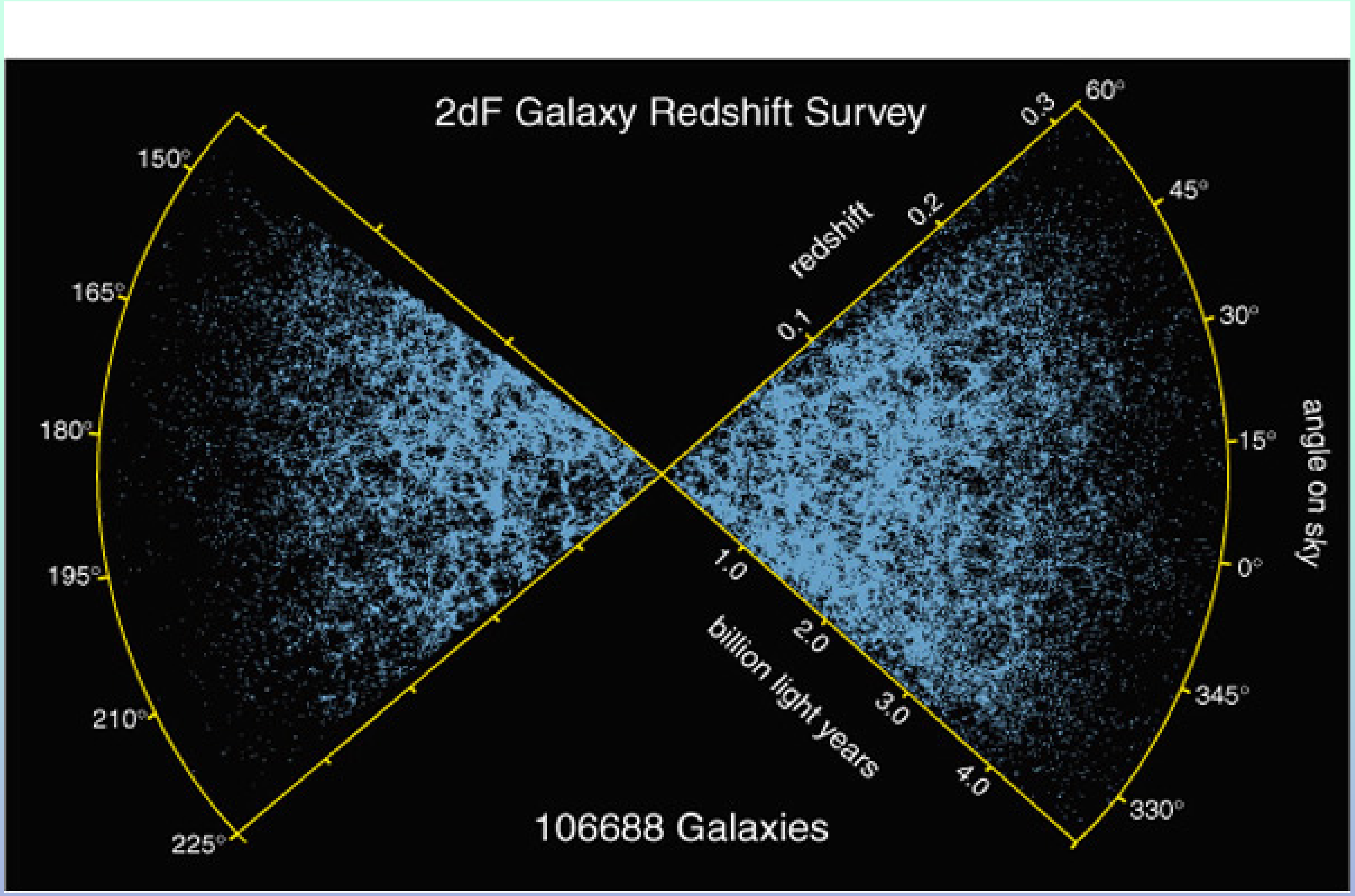



# Galaxies are Found in Clusters and Super-clusters of galaxies

# The universe within about 1000 million light-years around Earth



# The observable universe at billion light-years distances



# Possibility I: A new unknown form of energy

Particle physicists and cosmologists call it Dark Energy

Possible candidates are:

1) vacuum energy. Yes, the nature of vacuum is a very profound question.

2) A cosmological constant of nature.

3) quintessence scalar field due to other proposed ideas

Thousands of scientific publications on this topic.
NASA, National Science Foundation, and Department of Energy
all ranked this among the top current scientific questions.

# Possibility I: it is mathematically possible to have an energy with properties that will make the universe expand in an accelerating way. Trust me on this one.

(e.g. Upadhye, Ishak, Steinhardt, PRD 2005; Ishak, MNRAS 2005; Ishak, Found. of Physics 2008)

Can produce a cosmic acceleration because of their equation of state once put into Einstein's equations

The equation of state of the "cosmic fluid": $p = w\rho$

- for dust (= galaxies) (i.e. zero pressure) w=0
- for radiation w=1/3
- for a cosmological constant or vacuum energy w=-1

Other Dark Energy models can have w constant or w(t)

Negative w < -1/3 gives an accelerating expansion

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi}{3}(\rho_{DE} + 3p_{DE})$$

$$\frac{\ddot{a}(t)}{a(t)} = -4\pi\rho_{DE}(\frac{1}{3} + w)$$

## Possibility II:

## A geometrical constant of nature in the Einstein's equations. Just like Newton constant.

(e.g. Upadhye, Ishak, Steinhardt, PRD 2005; Ishak, MNRAS 2005; Ishak, Found. of Physics 2008)

$$G_b^a = \kappa T_b^a \qquad\qquad G_b^a + \Lambda \delta_b^a = \kappa T_b^a$$

These give the Friedmann equations with a cosmological constant

$$H^2(t) = \left( \frac{\dot{a}(t)}{a(t)} \right)^2 = \frac{8\pi\rho}{3} - \frac{k}{a(t)^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}(t)}{a(t)} = \frac{\Lambda}{3} - \frac{4\pi}{3}(\rho + 3p)$$

Λ is then just a constant of nature that we measure like Newton's constant, G. This is satisfactory for General Relativity but not for Quantum Field Theory and Unified theories of physics.

# Possibility III: Gravitation Beyond General Relativity of Einstein

- Extensions to General Relativity that take effect at the largest scales of the universe

- Another theory replaces General Relativity at very large scales in the universe

## Possibility III: Example of modifications or extensions to General Relativity: Higher order gravity models e.g. **Ishak and Moldenhauer, JCAP 2009a; Moldenhauer and Ishak, JCAP 2009b, 2010)**. We can skip the details.

- General Relativity is derived from variation of the Ricci scalar

$$S = \frac{M_p}{2}\int d^4x\sqrt{-g}R + \int d^4x\sqrt{-g}L_m$$

$$G_{\alpha\beta} = R_{\alpha\beta} - \frac{1}{2}R\,g_{\alpha\beta} = \frac{1}{M_p^2}T_{\alpha\beta}.$$

- Higher order gravity models are derived from functions of curvature invariants including the Ricci scalar but also other invariants (e.g. Carroll et al. PRD, 2003). Many papers looked at the so-called f(R) models

$$S = \frac{M_p}{2}\int d^4x\sqrt{-g}f(R, R^{\alpha\beta}R_{\alpha\beta}, R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta}, R^{\alpha\gamma}R_{\alpha\beta}R^{\beta}_{\gamma}, R^{\alpha\beta\mu\nu}R_{\alpha\beta\gamma\delta}R^{\gamma\delta}{}_{\mu\nu}, ...) + \int d^4x\sqrt{-g}L_m$$

- The field equations look like this (e.g. **Ishak and Moldenhauer, JCAP 2009a; Moldenhauer and Ishak, JCAP 2009b, 2010)**
- .

$$S^{\alpha\beta} - \frac{1}{4}g^{\alpha\beta}R - \frac{1}{2}g^{\alpha\beta}f + f_R S^{\alpha\beta} + \frac{1}{4}f_R g^{\alpha\beta}R + g^{\alpha\beta}f_{R;\gamma}{}^{\gamma} - f_{R;}{}^{\alpha\beta} + \frac{1}{2}f_{R1}S^{\alpha\gamma}S^{\beta}{}_{\gamma} + \frac{1}{8}f_{R1}S^{\alpha\beta}R$$
$$+\frac{1}{4}(f_{R1}S^{\alpha\beta})_{;\gamma}{}^{\gamma} + \frac{1}{4}g^{\alpha\beta}(f_{R1}S^{\gamma\delta})_{;\gamma\delta} - \frac{1}{4}(f_{R1}S^{\gamma\beta})_{;}{}^{\alpha}{}_{\gamma} - \frac{1}{4}(f_{R1}S^{\gamma\alpha})_{;}{}^{\beta}{}_{\gamma} = 8\pi G T^{\alpha\beta},$$

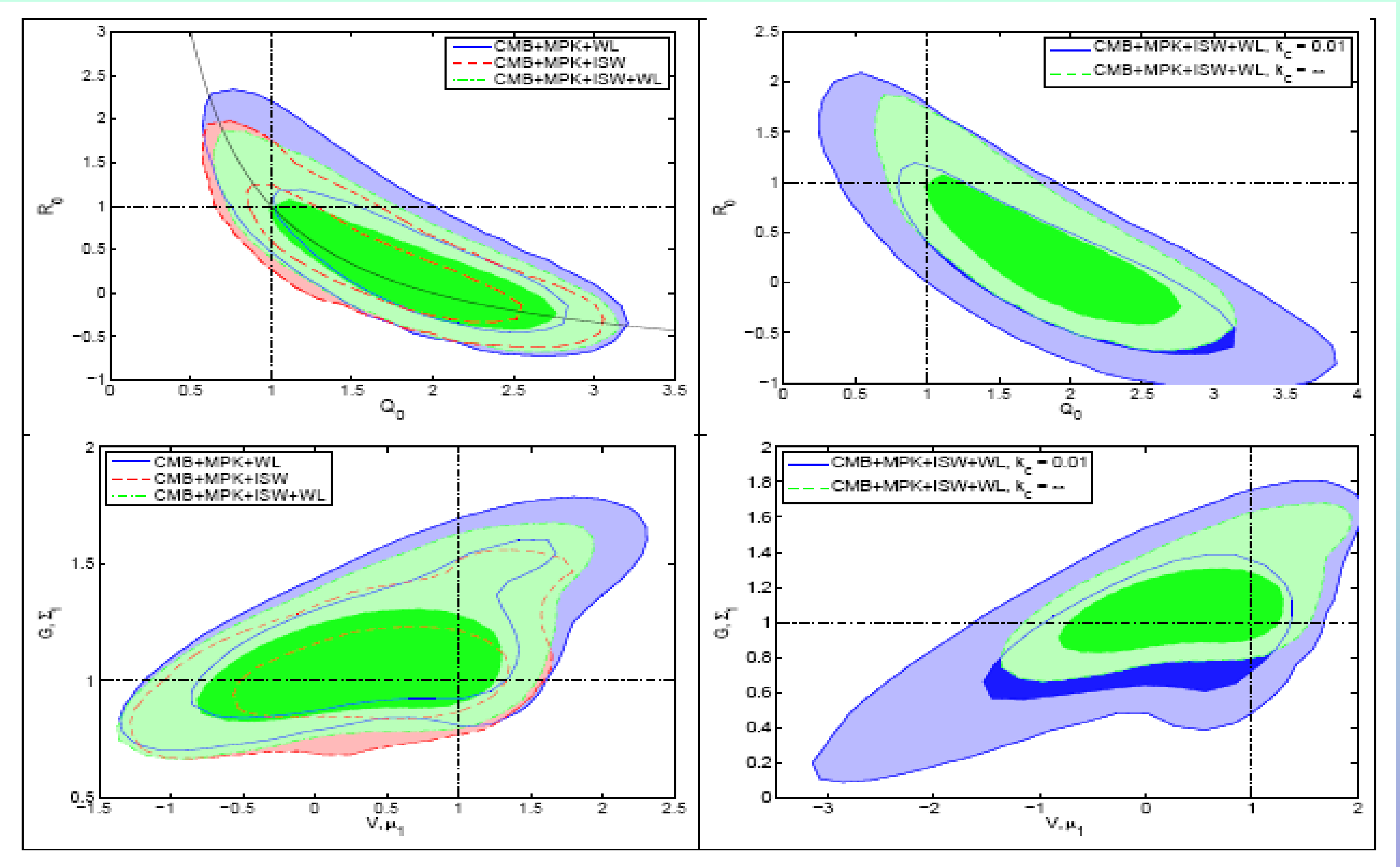
# Testing General Relativity at Cosmological scales using available observations

- Using probes of the expansion of the universe
- Using probes of the history of structure formation in the universe
- Using consistency tests between the two probes.

Using the latest cosmological data sets including refined COSMOS 3D weak lensing (Jason Dossett, Jacob Moldenhauer, Mustapha Ishak)

Phys.Rev.D84:023012,2011

No apparent deviation from GR using current data. More precise data coming.



# ISiTGR:
# Integrated Software in Testing General Relativity

**Version 1.1**

Developed by **Jason Dossett**, **Mustapha Ishak**, and **Jacob Moldenhauer**.

## What is ISiTGR?

ISiTGR is an integrated set of modified modules for the software package CosmoMC for use in testing whether observational data is consistent with general relativity on cosmological scales. This latest version of the code has been updated to allow for the consideration of non-flat universes. It incorporates modifications to the codes: CAMB, CosmoMC, the ISW-galaxy cross correlation likelihood code of Ho et al, and our own weak lensing likelihood code for the refined COSMOS 3D weak lensing tomography of Schrabback et al to test general relativity.

A detailed explanation of the modifications made to these codes allowing one to test general relativity are described in our papers: arXiv:1109.4583 and arXiv:1205.2422.

## How to get ISiTGR

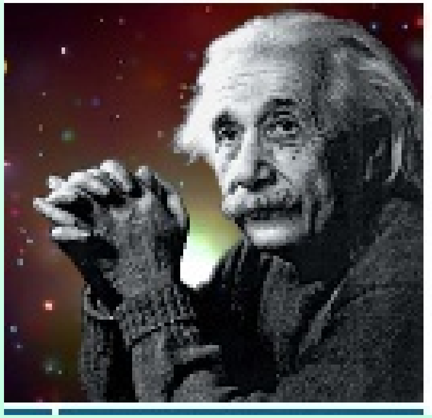
Two versions of ISiTGR are available. The normal version of ISiTGR uses a functional form to evolve the parameters used to test general relativity and is available here. ISiTGR_BIN, on the other hand, gives you two options to evovle the parameters used to test general relativity. The first option is to bin the parameters in two redshift and two scale bins, alternatively one can use the hybrid evolution method, as seen in our paper, where scale dependence evolves monotonically, but redshift dependence is binned. That code can be downloaded here.

**Download Here:** ISiTGR ISiTGR_BIN

The original (flat only) verison of ISiTGR as well as builds for other versions of CosmoMC are available here (**this version is for CosmoMC 01/2012**).

# Recap: Possible Causes of Cosmic Acceleration

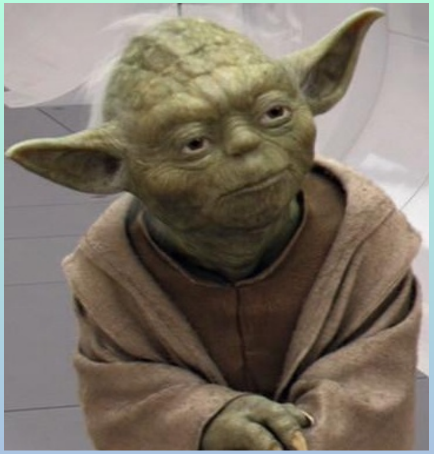
- Proposed possibilities in thousands of scientific publications:
  - A dark energy component
  - GR cosmological constant
  - A modification to general relativity at cosmological scales; Higher dimensional physics
  - → Apparent acceleration due to the fact that we live in a relativistic cosmological model more complex than FLRW



# *Possibility IV:*
## *"May General Relativity Be With You"*
*(Jedi Einstein)*

- **A fourth possibility: Apparent acceleration due to the fact that we live in a relativistic cosmological model more complex than FLRW**
- GR history is full of surprises: starting from the prediction of a non-static expanding universe which already encountered some resistance

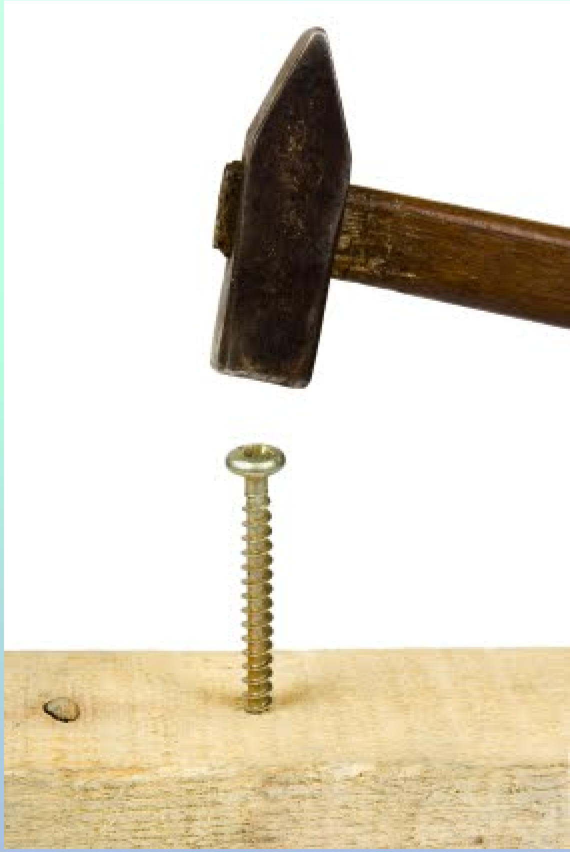
*"May the force be with you" , (Jedi Yoda)*



**Today: Dark Side times (Dark Energy, Dark Matter, Cosmological constant, Modified Gravity models…)**

# *Do we have the right model in hands?*

- We can't explain ~70% (or~95%) of the observed dynamics
- Observations of the expansion rate of Supernovae can have different interpretations in FLRW versus an Inhomogeneous model
- Do we live in a complex and subtle general relativistic cosmological model?
- Is the FLRW model limiting our ability to interpret observations?
- Well motivated questions in view of the non-linearity of GR, and the unsolved averaging problem in cosmology



# Observations in inhomogeneous models and the null geodesic equations (not radial)

Now we know why people did not work on these models before

$$\frac{d^2t}{d\lambda^2}+\frac{R_{,tr}-R_{,t}E_{,r}}{1-k}\left(R_{,r}-\frac{RE_{,r}}{E}\right)\left(\frac{dr}{d\lambda}\right)^2+\frac{RR_{,t}}{E^2}\left[\left(\frac{dp}{d\lambda}\right)^2+\left(\frac{dq}{d\lambda}\right)^2\right]=0$$

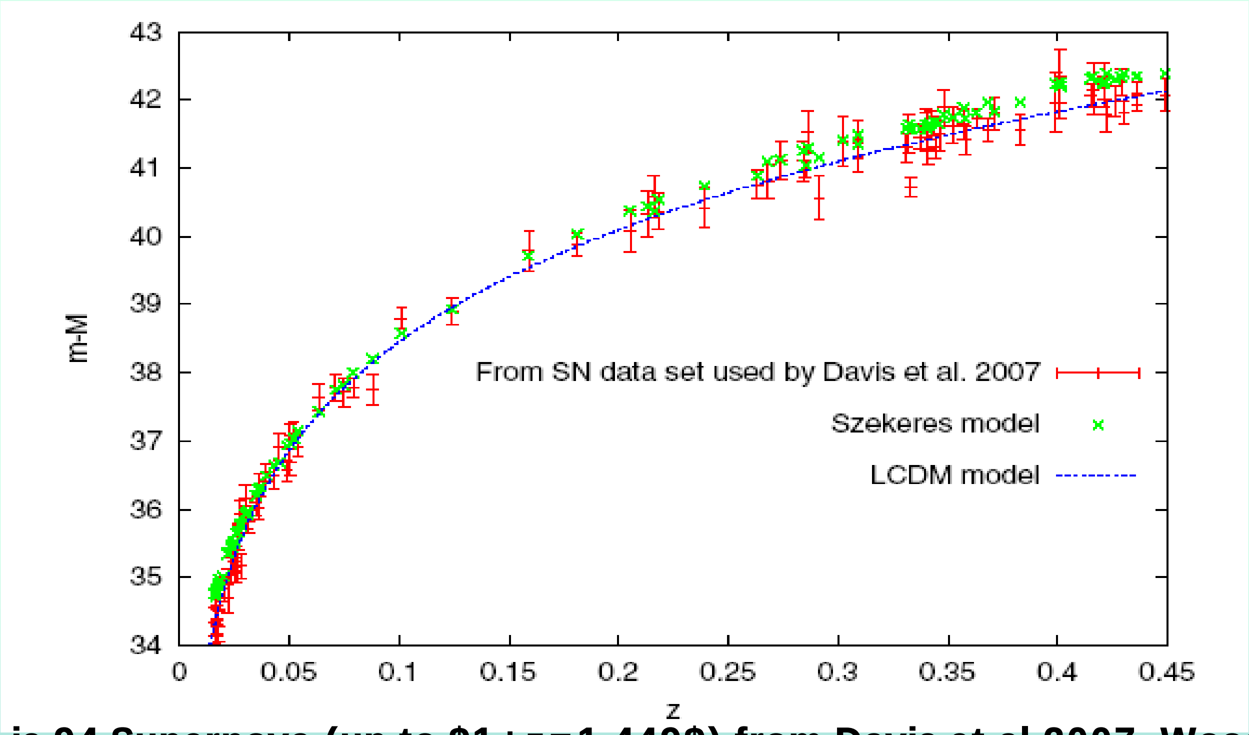
$$\frac{d^2r}{d\lambda^2}+\left(2\frac{R_{,tr}-\frac{R_{,t}E_{,r}}{E}}{R_{,r}-\frac{RE_{,r}}{E}}\right)\left(\frac{dt}{d\lambda}\frac{dr}{d\lambda}\right)+\left(\frac{R_{,rr}-\frac{R_{,r}E_{,r}}{E}-\frac{RE_{,rr}}{E}+R\left(\frac{E_{,r}}{E}\right)^2}{R_{,r}-\frac{RE_{,r}}{E}}+\frac{k_{,r}}{2(1-k)}\right)\left(\frac{dr}{d\lambda}\right)^2$$

$$+\left(2\frac{R}{E^2}\frac{E_{,r}E_{,p}-EE_{,pr}}{R_{,r}-\frac{RE_{,r}}{E}}\right)\left(\frac{dr}{d\lambda}\frac{dp}{d\lambda}\right)+\left(2\frac{R}{E^2}\frac{E_{,r}E_{,q}-EE_{,qr}}{R_{,r}-\frac{RE_{,r}}{E}}\right)\left(\frac{dr}{d\lambda}\frac{dq}{d\lambda}\right)-\frac{R}{E^2}\frac{1-k}{R_{,r}-\frac{RE_{,r}}{E}}\left[\left(\frac{dp}{d\lambda}\right)^2+\left(\frac{dq}{d\lambda}\right)^2\right]=0$$

$$\frac{d^2p}{d\lambda^2}+2\frac{R_{,t}}{R}\left(\frac{dt}{d\lambda}\frac{dp}{d\lambda}\right)-\left(\frac{R_{,r}-\frac{RE_{,r}}{E}}{R(1-k)}\left(E_{,r}E_{,p}-EE_{,pr}\right)\right)\left(\frac{dr}{d\lambda}\right)^2+2\left(\frac{R_{,r}}{R}-\frac{E_{,r}}{E}\right)\left(\frac{dr}{d\lambda}\frac{dp}{d\lambda}\right)-\frac{E_{,p}}{E}\left(\frac{dp}{d\lambda}\right)^2-2\frac{E_{,q}}{E}\left(\frac{dp}{d\lambda}\frac{dq}{d\lambda}\right)+\frac{E_{,p}}{E}\left(\frac{dq}{d\lambda}\right)^2=0$$

$$\frac{d^2q}{d\lambda^2}+2\frac{R_{,t}}{R}\left(\frac{dt}{d\lambda}\frac{dq}{d\lambda}\right)-\left(\frac{R_{,r}-\frac{RE_{,r}}{E}}{R(1-k)}\left(E_{,r}E_{,q}-EE_{,qr}\right)\right)\left(\frac{dr}{d\lambda}\right)^2+2\left(\frac{R_{,r}}{R}-\frac{E_{,r}}{E}\right)\left(\frac{dr}{d\lambda}\frac{dq}{d\lambda}\right)+\frac{E_{,q}}{E}\left(\frac{dp}{d\lambda}\right)^2-2\frac{E_{,q}}{E}\left(\frac{dp}{d\lambda}\frac{dq}{d\lambda}\right)-\frac{E_{,q}}{E}\left(\frac{dq}{d\lambda}\right)^2=0$$

Results: Ishak et al. Phys. Rev. D 78, 123531 (2008)




- The data is 94 Supernova (up to $1+z=1.449$) from Davis et al 2007, Wood-Vasey et al 2007, and Riess et al 2007
- The Szekeres model fits the data with a chi^2=112. This is close to the chi^2=105 of the LCDM concordance FLRW model.
- Because of the possible systematic uncertainties in the supernova data, it is not clear that the difference between the two chi^2 and fits is significant. And we did not explore all the Szekeres models
- The Szekeres model used is also consistent with the requirement of spatial flatness at CMB scales.

Title: Luminosity distance and redshift in the Szekeres inhomogeneous cosmological models

Nwankwo, Ishak, Thompson JCAP 1105:028, (2011)

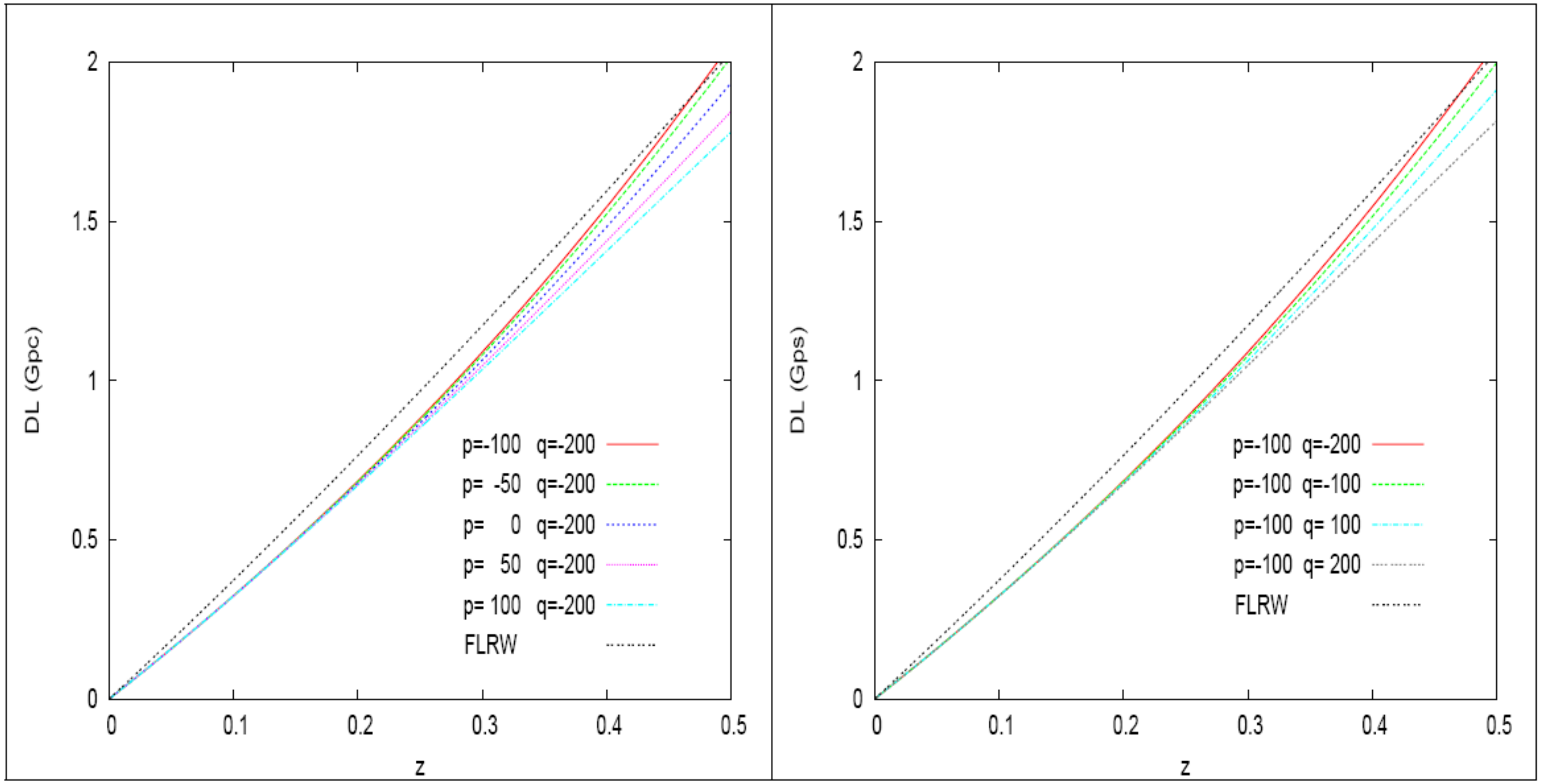
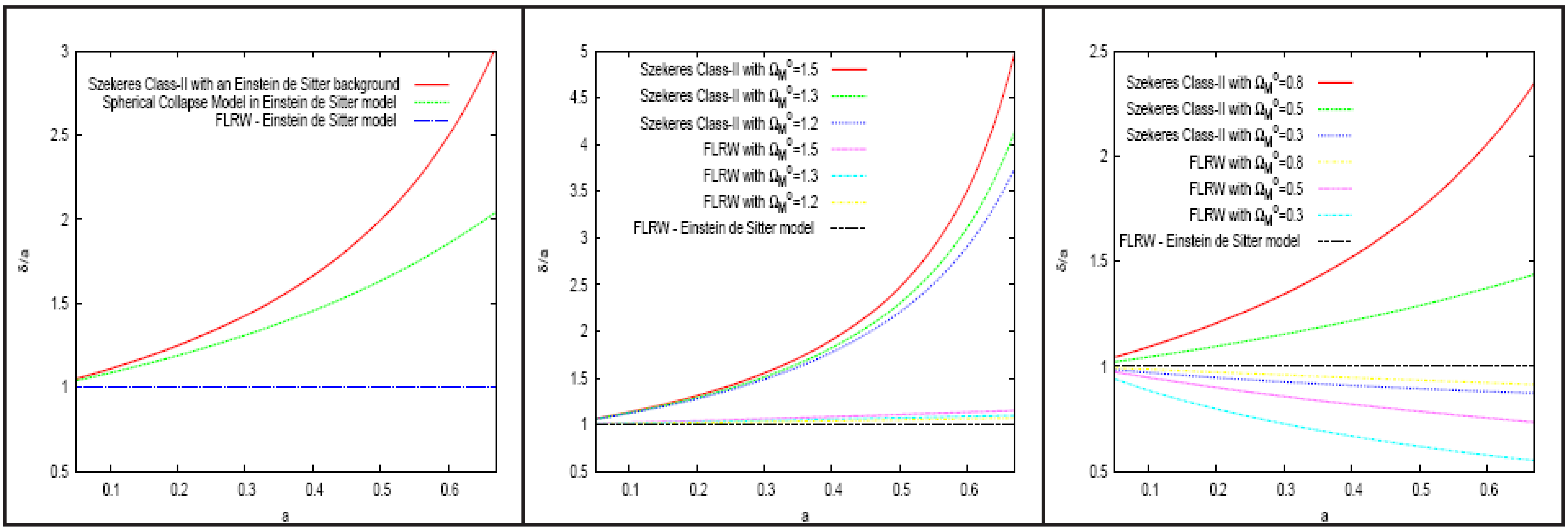



FIG. 1: Luminosity distances for a Szekeres model that is not axially or spherically symmetric. To the left, the value of $q$ is fixed to $-200$ while $p$ is varied by taking the values $-100, -50, 0, 50, 100$. To the right, the value of $p$ is fixed to $-100$ while $p$ is varied by taking the values $-200, -100, 0, 100, 200$. The Szekeres inhomogeneous model used here is for illustration purposes only and is specified in section V-A. The luminosity distance for an open FLRW model is plotted as well.

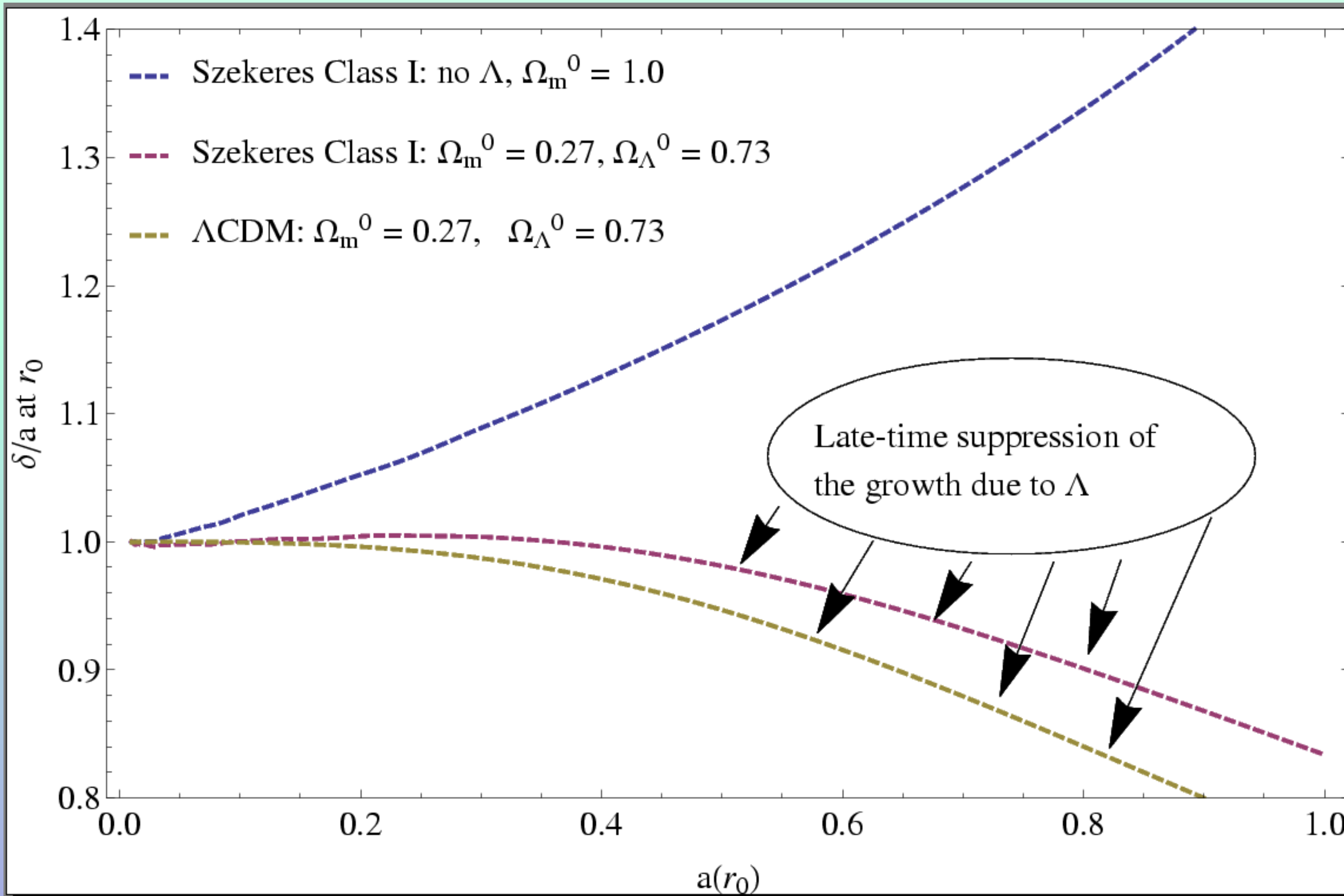
# Exploring the growth of large scale structure using Szekeres models.

Ishak, Peel, PRD 2012; Peel, Ishak, Troxel, PRD submitted 2012; more to come

$$G'' + \left(4 - \frac{\Omega_M(a)}{2}\right)\frac{G'}{a} + 2(1-\Omega_M(a))\frac{G}{a^2} - \frac{2}{a}\frac{(G+aG')^2}{1+aG} - \frac{3}{2}\Omega_M(a)\frac{G^2}{a} = 0.$$



# Possibility IV: excluded now
## Ishak, Peel, Troxel, PRD (2013)



# Last comment:

- Perhaps the answer to this cosmic puzzle will be completely unexpected and will provide a completely different picture of the nature of space and time.

# Recent Cosmology Graduate Students Joining the National and International Academia World






**Journal paper highlighted at the Physical Review Letters Journal**

Selected by the Editors for a synopsis in *Spotlighting Exceptional Research in Physics* on the website of the American Physical Society.

Article:
"Stringent Restriction from the Growth of Large-Scale Structure on Apparent acceleration in Inhomogeneous Cosmological Models",

Mustapha Ishak, Austin Peel, M. A. Troxel. Phys. Rev. Lett. 111, 251302 (2013).