Theoretical and Observational Confrontation of Cosmology and Gravity, and the New Era of Multi-messenger Astronomy

Emmanuel N. Saridakis

Physics Department, National and Technical University of Athens, Greece

Physics Department, Baylor University, Texas, USA

National Technical University of Athens

CANTATA

Cosmology and Astrophysics Network for Theoretical Advances and Training Actions

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Goal

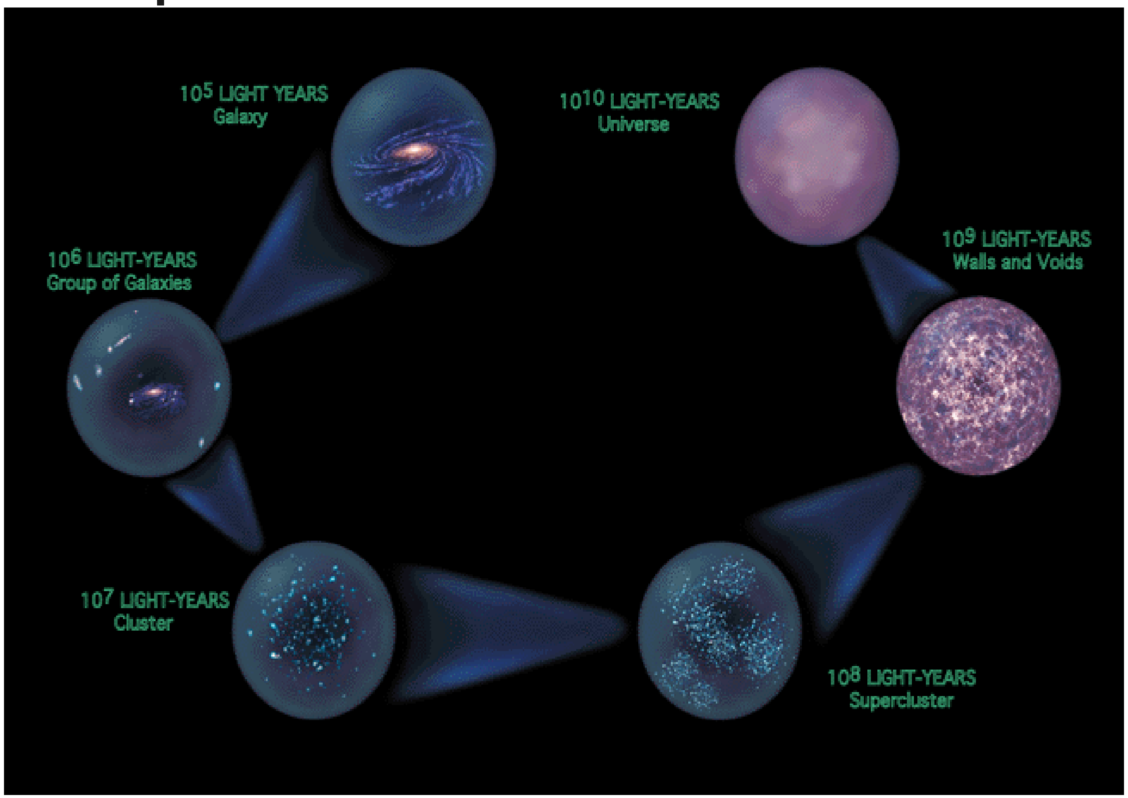
- We investigate cosmological scenarios that can describe the observed Universe as a whole

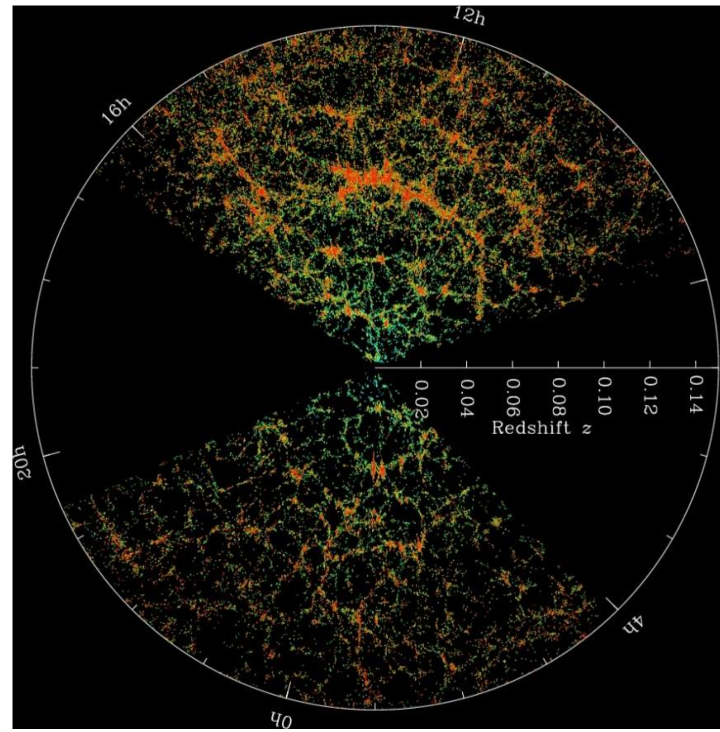
- Astrophysical cosmology has become a precision science with a huge amount of data. The advancing gravitational wave multi-messenger astronomy opens a new era

Talk Plan

- 1) Observational Cosmology: the Standard Model of Cosmology.
- 2) Standard Model of Cosmology. Do we need new physics?
- 3) We can modify the Universe content, or/and the gravitational theory.
- 4) Use of various observational data (SnIa, CMB, BAO, H(z), LSS etc) in order to constrain the proposed theories.
- 5) GWs: basic properties and evolution.
- 6) Gravitational wave astronomy, and multi-messenger astronomy: a novel tool to test General Relativity and cosmological scenarios in great accuracy.

Observations





- SDSS (Sloan Digital Sky Survey) 2004: ~ clusters "above and below the galactic plane" up to 1 Gpc

Observations

- As the scale we observe the Universe increases, it looks as homogeneous and isotropic.

- Cosmological Principle: "axiom" (indirect result)

  I) We know that earth is an isotropic observation point.

  II) An anisotropic system has up to one isotropic observation point.

- Hence, either we lie in the only isotropic observation point in an anisotropic Universe, or all its points are isotropic observation points.

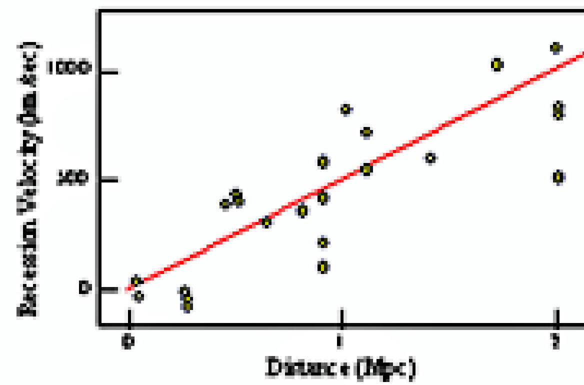
- Thus, the Universe is homogeneous and isotropic (isotropic and inhomogeneous is not possible)

Observations

- Hubble 1929: The Universe expands

Hubble excelled in every course at school (except spelling), but was better known for his athletic prowess. He was a star player in football, baseball, and basketball, and ran track in high school and at the University of Chicago, where he earned a Bachelor of Science in 1910.

Hubble's Data (1929)



$$v = H\ r$$

$$H_0 \approx 70\ km\ s^{-1}\ Mpc^{-1}$$

Observations

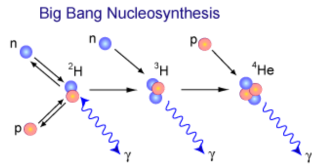
- Since the Universe expands it is reasonable that it originates from a "too tiny" and "too dense" "primordial atom" (Lemaitre 1927)

- Alpher, Bethe, Gamow (1948): The Universe begun to expand from a very high-density and high-temperature state towards less dense and hot states. Hoyle named the theory "The Big Bang Theory".

- **Prediction I**: Nucleosynthesis has primordial origin, namely at first 3 minutes ($\sim 10^9$ K) (giving 25% Helium) and not in stars (1-4%) As observed.

Observations

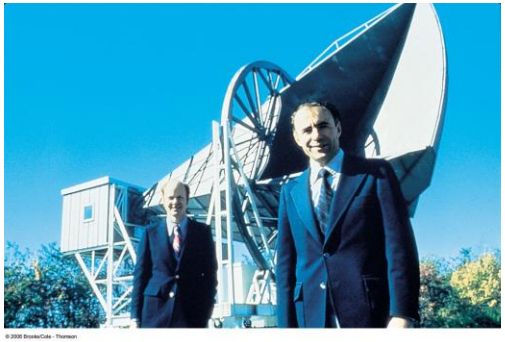
- **Prediction II**: The primordial Universe became full of high-energy photons

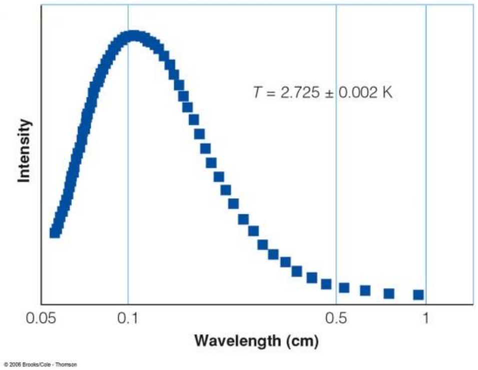


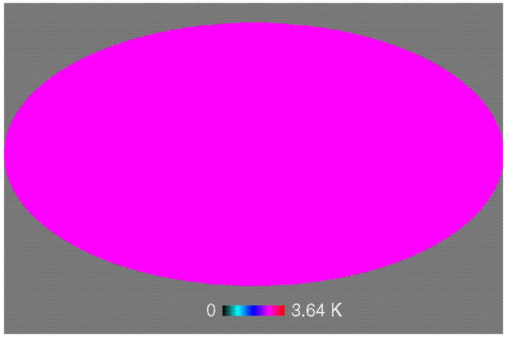
$\lambda \approx 7 \cdot 10^{-12}\ cm,$

380.000 years after (~3000K) they decouple from electrons (Recombination era). Black body radiation (today ~2.7 K)

- 1965 Penzias και Wilson







Theoretical arguments

- Big Bang Theory explained: Olbers paradox (1826) (why night sky is not bright), Ryle (1970) (Radio galaxies density increases with redshift), Element abundance, CMB, etc

- Theoretical Problems:

- I) Horizon problem: Why points at opposite directions have the same properties
- II) Flatness problem: Why the universe is today almost spatially flat Ω_k ~0.001. It must have started with $\sim 10^{-50}$!
- Monopole problem: They are not observed.

Inflation

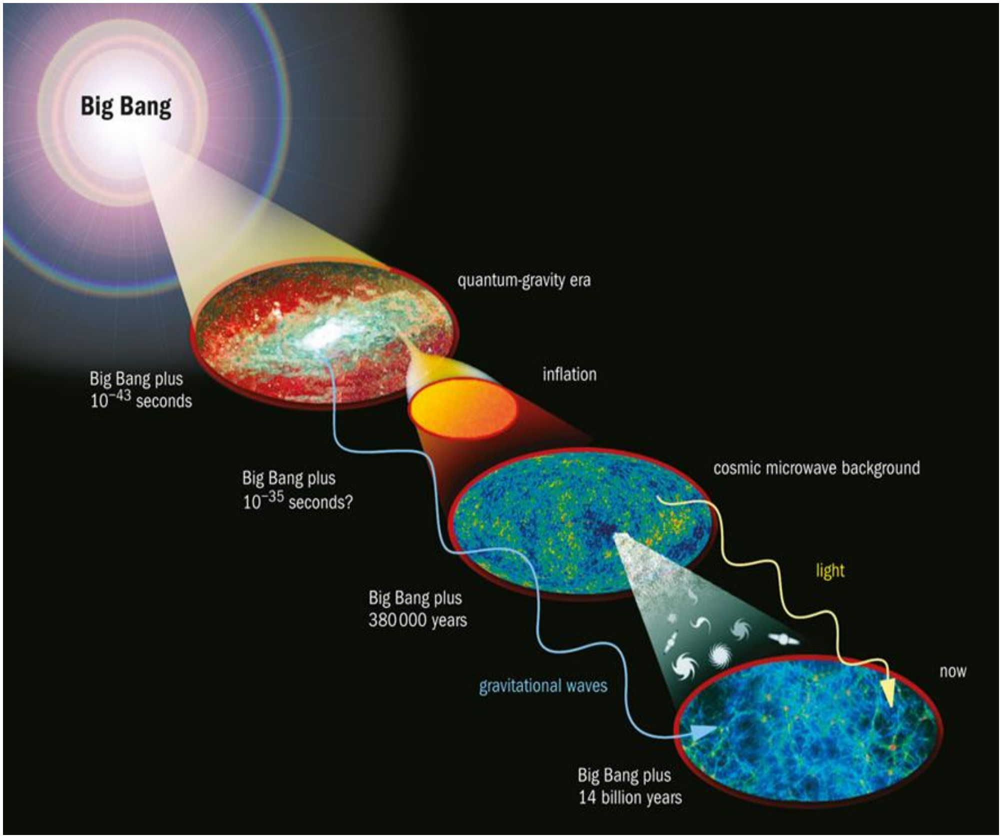
- Kazanas, Guth, Linde (1982): The Universe $10^{-36}\,\text{sec}$ after the Big Bang, through some mechanism went into an exponential expansion up to $10^{-32}\,\text{sec}$ increasing in size ~ 10^{30} times: Inflation.

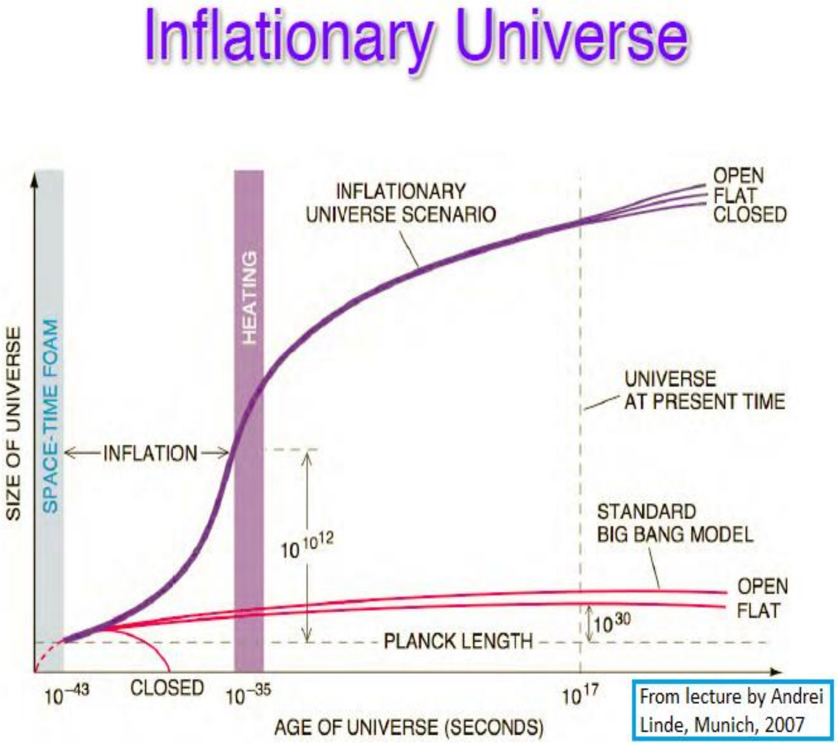
- I) The observable Universe is a tiny part of the total one, and originates from a small, causally connected region.

- II) Due to the huge expansion, the spatial curvature became almost zero.

- III) Due to the huge expansion the monopoles spread in all regions, and thus our own, observable universe, has at most one.

Inflation

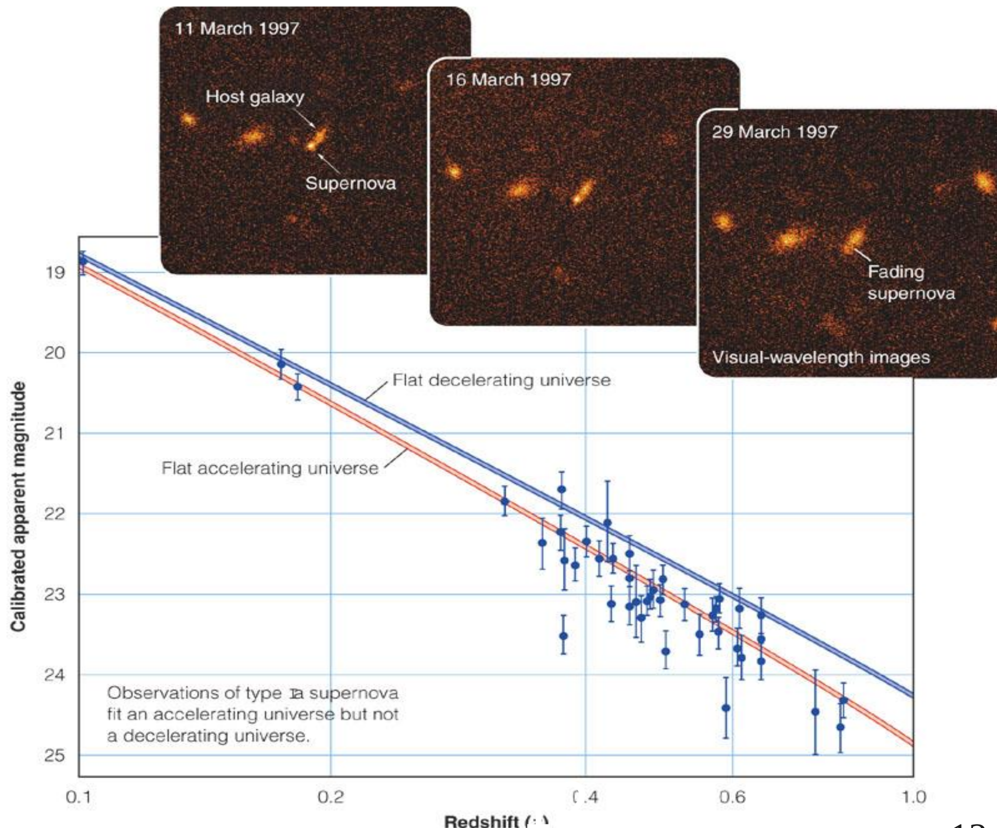

Big Bang
quantum-gravity era
Big Bang plus
10−43 seconds
inflation
Big Bang plus
10−35 seconds?
cosmic microwave background
light
Big Bang plus
380 000 years
gravitational waves
now
Big Bang plus
14 billion years


Inflationary Universe
SIZE OF UNIVERSE
SPACE-TIME FOAM
HEATING
INFLATIONARY
UNIVERSE SCENARIO
OPEN
FLAT
CLOSED
UNIVERSE
AT PRESENT TIME
INFLATION
10^10^12
STANDARD
BIG BANG MODEL
OPEN
FLAT
10^30
PLANCK LENGTH
10−43
CLOSED
10−35
10^17
AGE OF UNIVERSE (SECONDS)
From lecture by Andrei
Linde, Munich, 2007

Dark Energy

- The Supernovae type Ia (explosions of binaries with one being white dwarf) are "standard candles", since their absolute magnitude M can be determined.

- In 1998 οι Perlmutter, Schmidt, Riess observed that 50 SnIa had smaller apparent magnitude than expected hence light traveled more, and thus the Universe today expands faster than before!



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Dark Energy

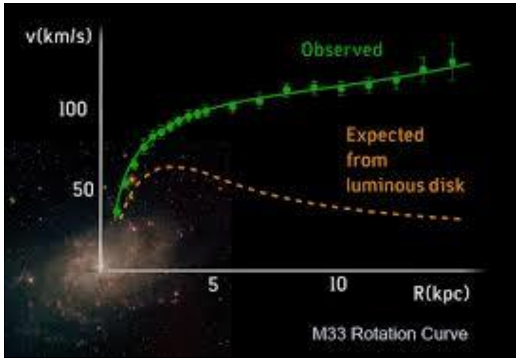
- The accelerated expansion is verified by independent observations, Cosmic Microwave Background (CMB), Baryon Acoustic Oscillations (BAO), Large Scale Structure (LSS), etc

- Around 70% of the total energy density of the Universe is this unknown dark energy (it does not interact electromagnetically).

- Possible explanation: The cosmological constant Λ (Einstein's "greatest blunder"). A term that produces the extra "repulsion".

Dark Matter

- Galaxy rotation curves:



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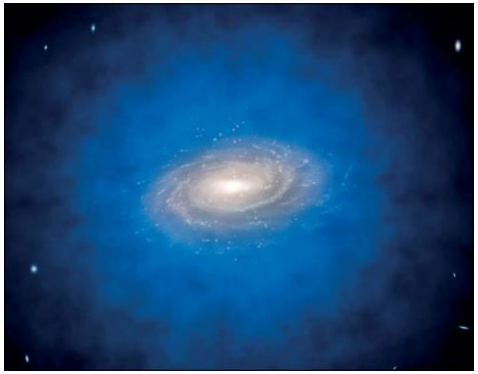
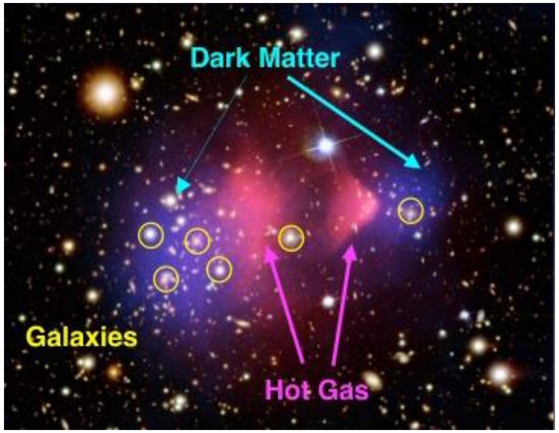


- Bullet cluster (collision of two galaxy clusters)



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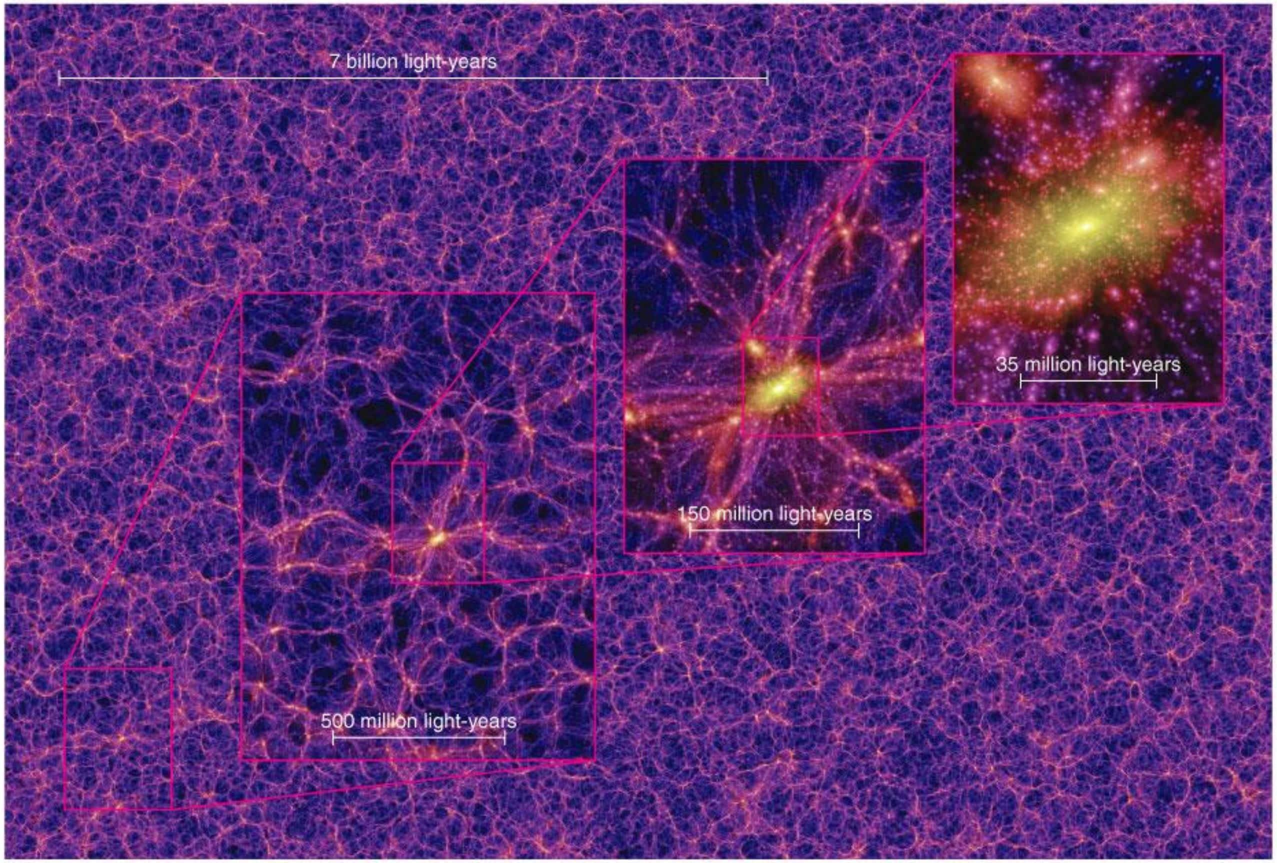
- 80% of matter is an "unknown" dark matter (it does not interact electromagnetically)!

Dark Matter



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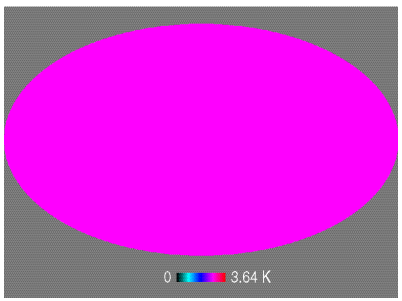
Cosmic Microwave Background radiation

- Since 1989, COBE, WMAP και Planck satellites show that CMB has small fluctuations:



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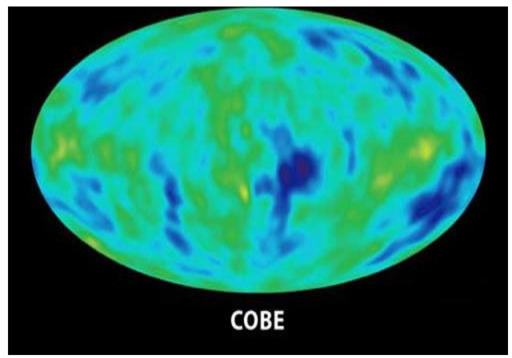

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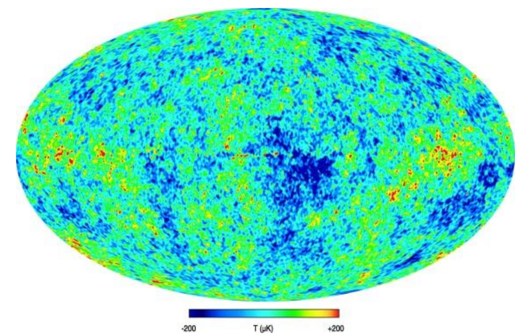

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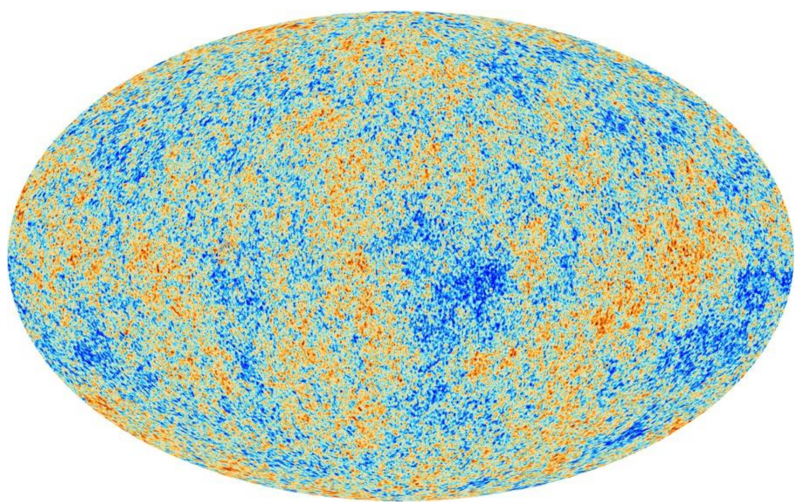
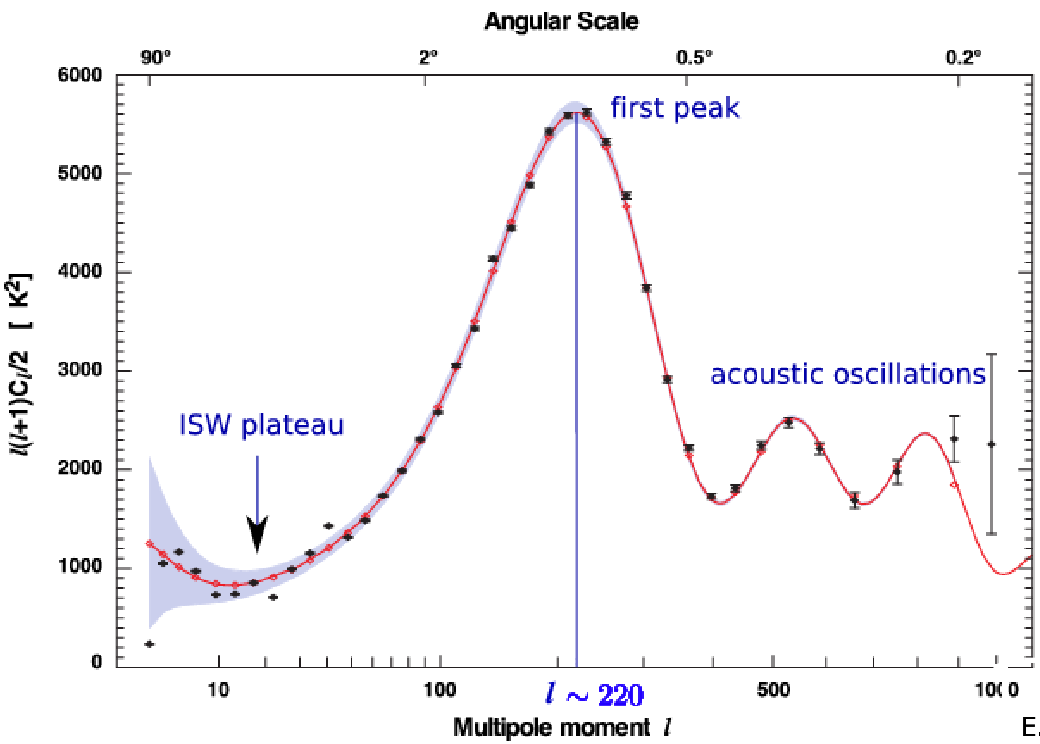


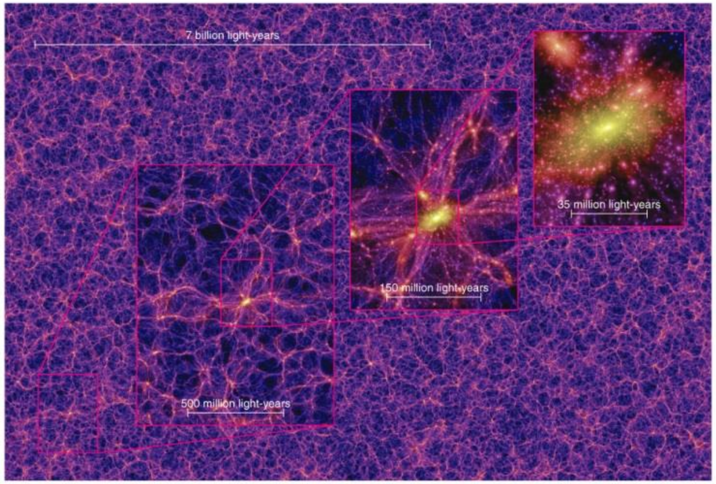
Cosmic Microwave Background radiation

- From the fluctuation spectrum we extract information: The first peak provides the spatial curvature (it results to flat universe), the second peak the baryon energy density parameter, the third peak the dark matter energy density parameter, etc.



Inflation can also explain CMB and seeds of LSS

- Additional success: Inflation provides the necessary primordial fluctuations, which letter gave the Large Scale Structure of matter:



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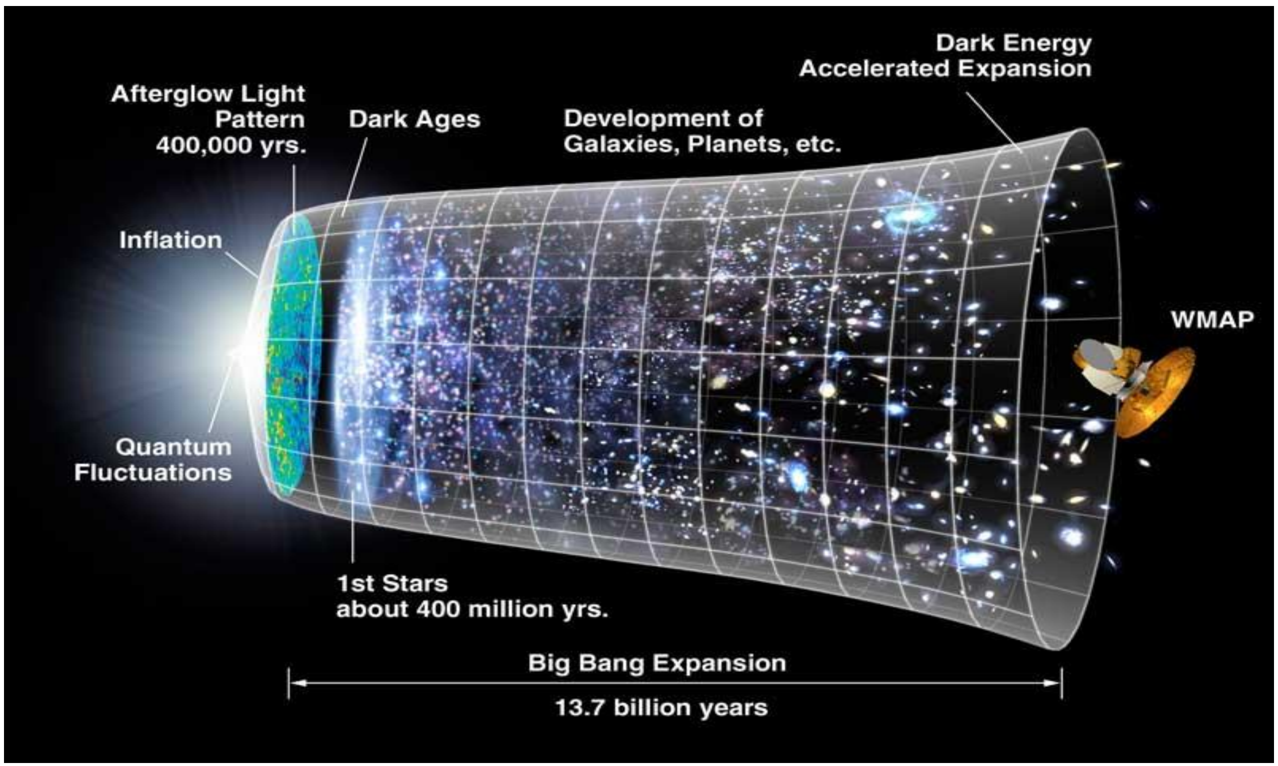
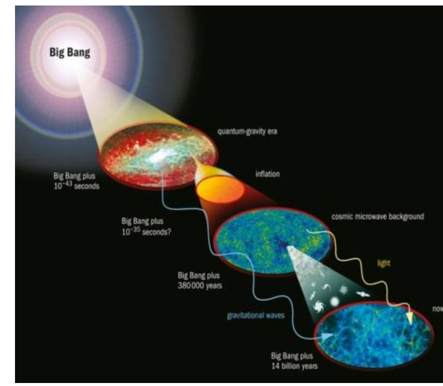
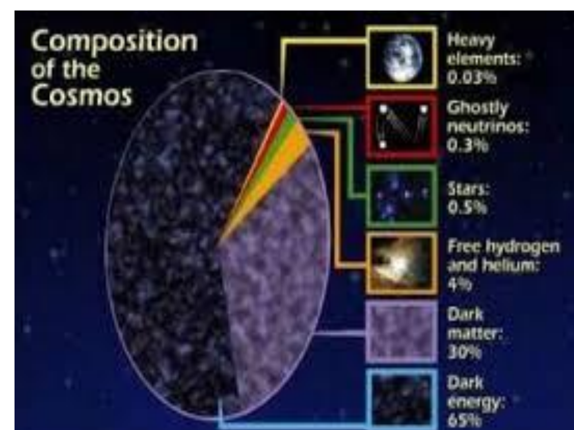
Summary of Observations

The Universe history:

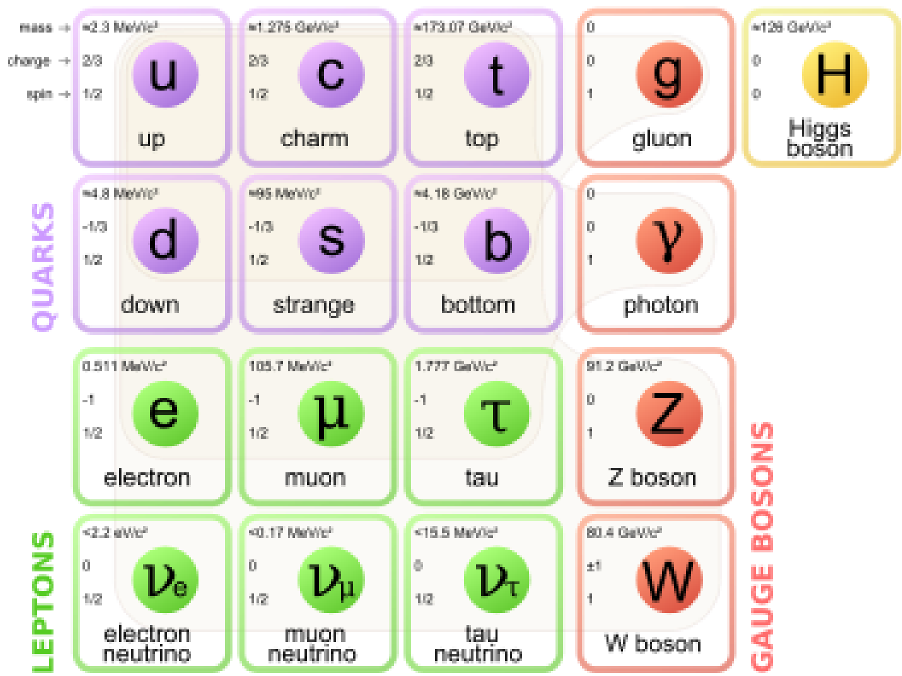






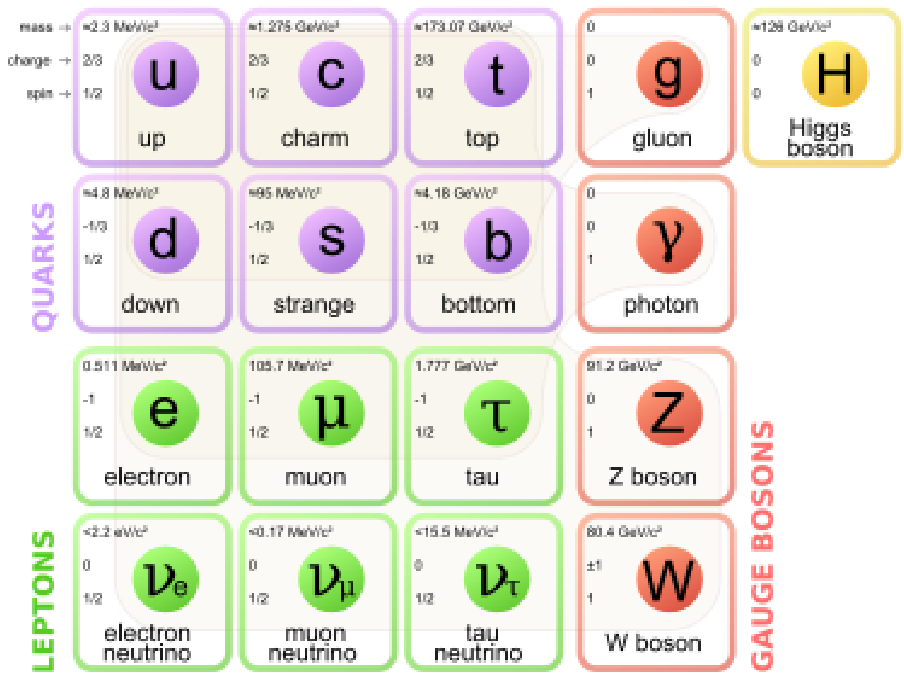
Knowledge of Physics

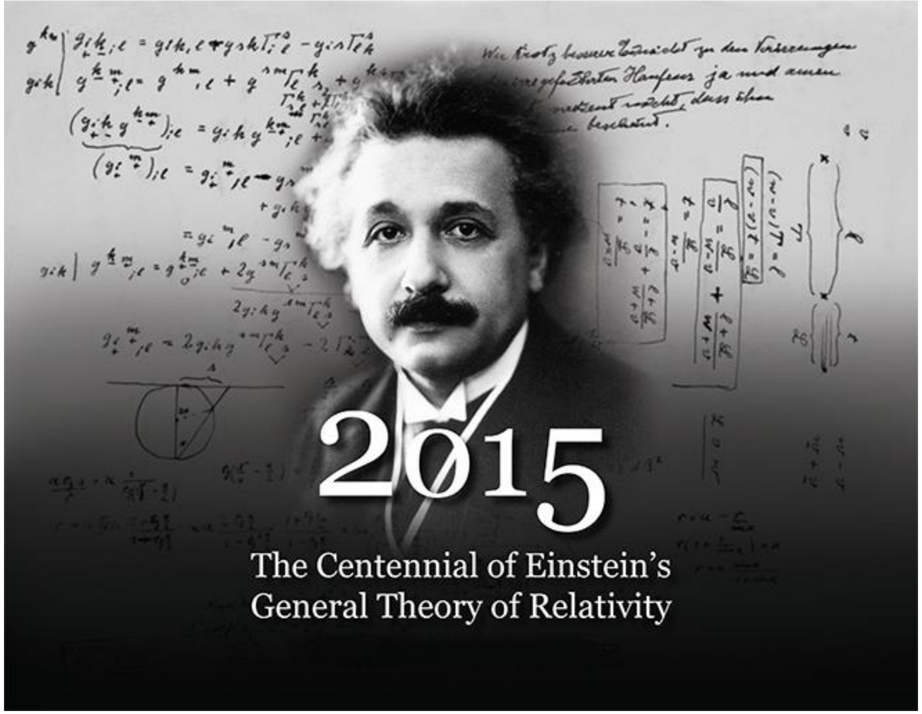
Knowledge of Physics: Standard Model



Knowledge of Physics

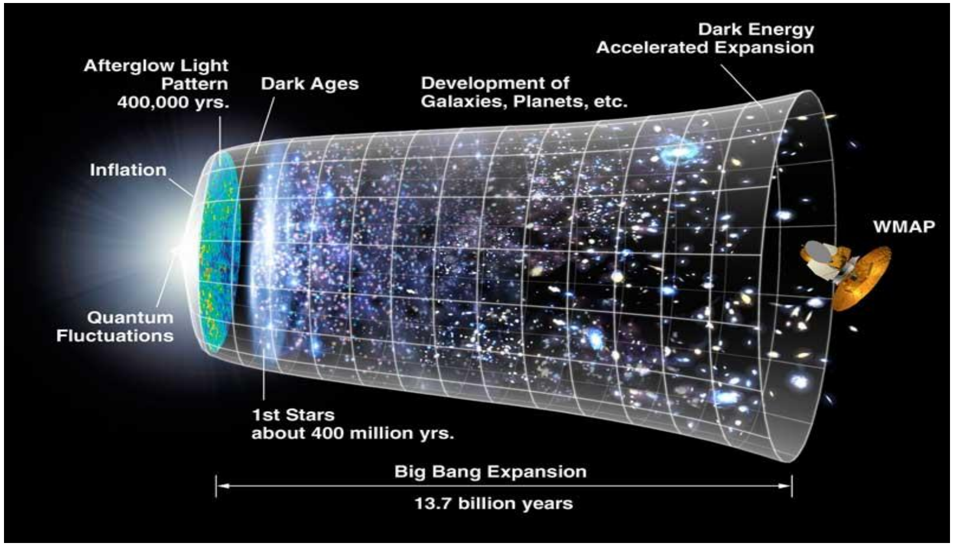
Knowledge of Physics: Standard Model + General Relativity

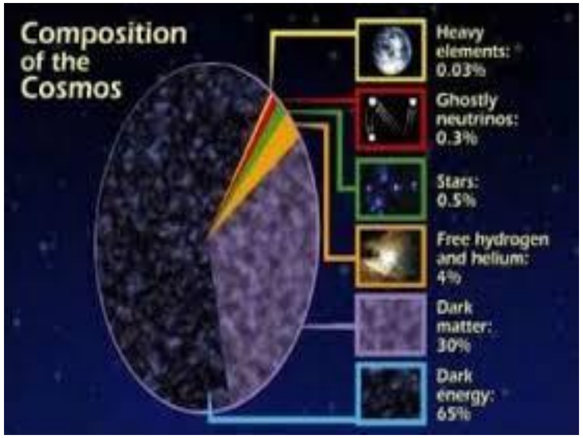




Modified/new knowledge of physics

So can our knowledge of Physics describes all these?





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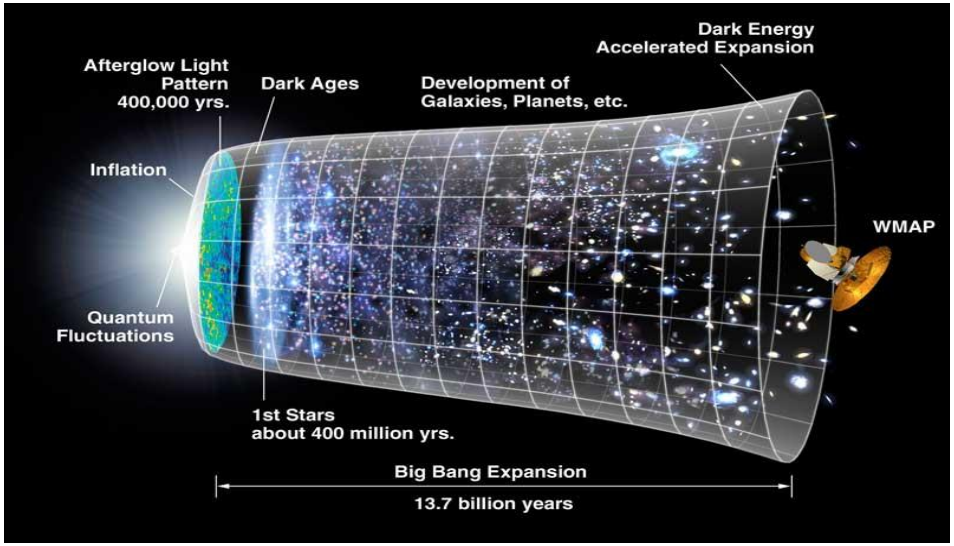
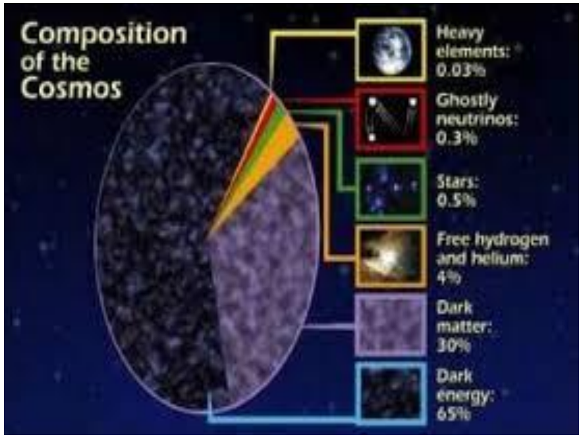




Most probably, no!

We definitely need new physics for Inflation and Dark matter. Maybe for dark energy.

Cosmology

- A successful cosmological model must:

1) Describe the evolution of the universe at the background level
2) Describe the evolution of the universe at the perturbation level

Cosmology

- A successful cosmological model must:

1) Describe the evolution of the universe at the background level
2) Describe the evolution of the universe at the perturbation level

- ΛCDM paradigm seems to succeed in both, at post-inflationary eras

- Open issues:
  1) The cosmological-constant problem. Calculation of Λ gives a number 120 orders of magnitude larger than observed.
     Worst error in the his~~tory of physics, h~~is~~tory of science, h~~istory
  2) How to describe primordial universe (inflation)
  3) Tensions with some data sets, e.g. H0 and $f\sigma_8$ data

Cosmology-background

- Homogeneity and isotropy: $ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$

- Background evolution (Friedmann equations) in flat space

$$H^2 = \frac{8\pi G}{3}\left(\rho_m + \rho_{DE}\right)$$
$$\dot{H} = -4\pi G\left(\rho_m + p_m + \rho_{DE} + p_{DE}\right),$$

(the effective DE sector can be either Λ or any possible modification)

- One must obtain a H(z) and Ωm(z) and wDE(z) in agreement with observations (SNIa, BAO, CMB shift parameter, H(z) etc)

Cosmology-perturbations

- Perturbation evolution: $\ddot{\delta} + 2H\dot{\delta} - 4\pi G_{\rm eff}\,\rho\,\delta \approx 0$ where $\delta \equiv \delta\rho/\rho$

  where $G_{\rm eff}(z,k)$ is the effective Newton's constant, given by

  $$\nabla^2\phi \approx 4\pi G_{\rm eff}\rho\,\delta,$$

  under the scalar metric perturbation $ds^2 = -(1+2\phi)dt^2 + a^2(1-2\psi)d\vec{x}^{\,2}$

- Hence: $$\delta'' + \left(\frac{(H^2)'}{2\,H^2} - \frac{1}{1+z}\right)\delta' \approx \frac{3}{2}(1+z)\frac{H_0^2}{H^2}\frac{G_{\rm eff}(z,k)}{G_N}\,\Omega_{0m}\delta$$

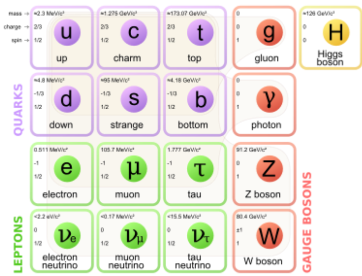
  with $f(a) = \frac{d\ln\delta}{d\ln a}$ the growth rate, with $f(a) = \Omega_{\rm m}(a)^{\gamma(a)}$ and $\Omega_{\rm m}(a) \equiv \frac{\Omega_{0m}\,a^{-3}}{H(a)^2/H_0^2}$

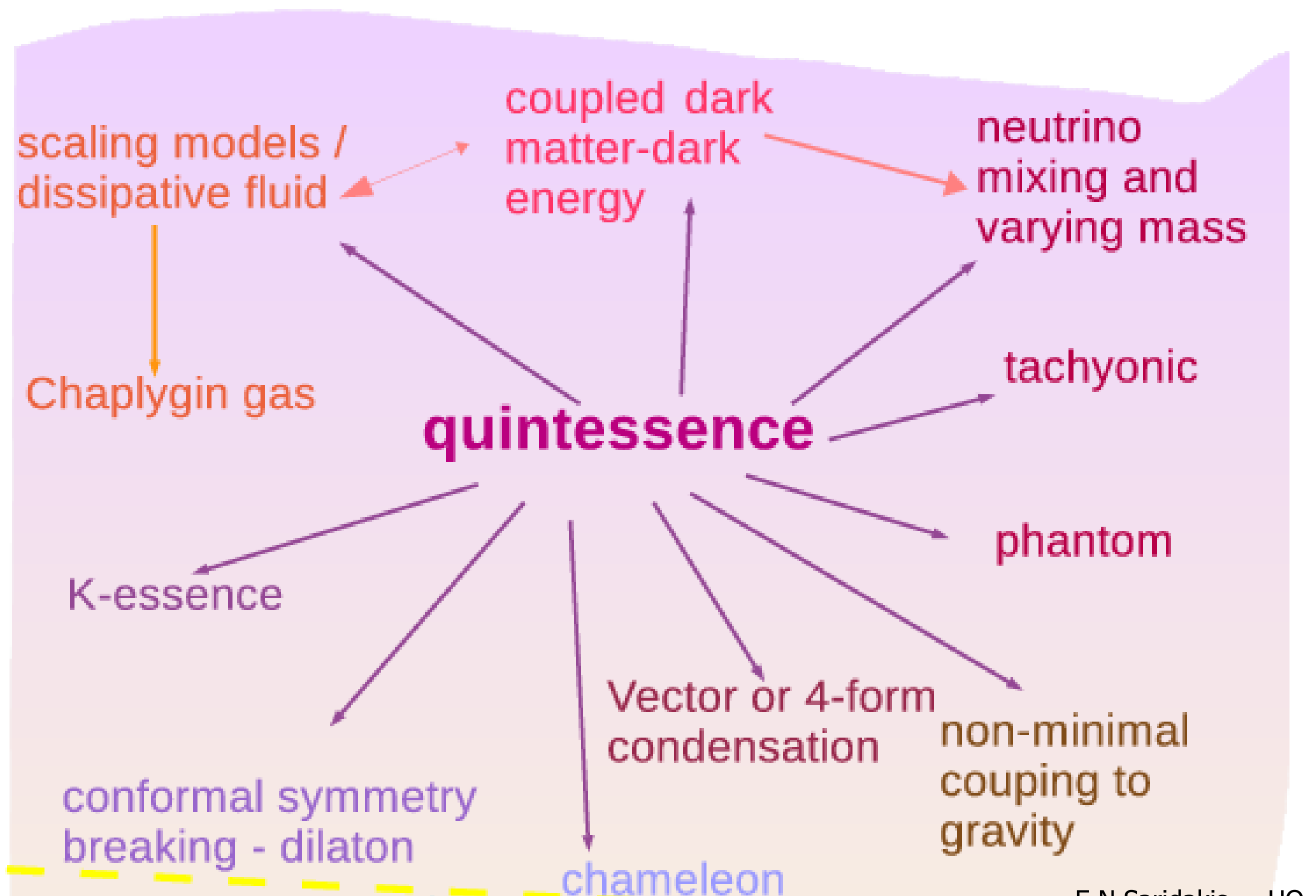
- One can define the observable: $f\sigma_8(a) \equiv f(a)\cdot\sigma(a) = \frac{\sigma_8}{\delta(1)}\;a\;\delta'(a)$

  with $\sigma(a) = \sigma_8\frac{\delta(a)}{\delta 1}$ the z-dependent rms fluctuations of the linear density field within spheres of radius $R = 8h^{-1}\mathrm{Mpc}$, and σ8 its value today.

Dark Energy-Inflation

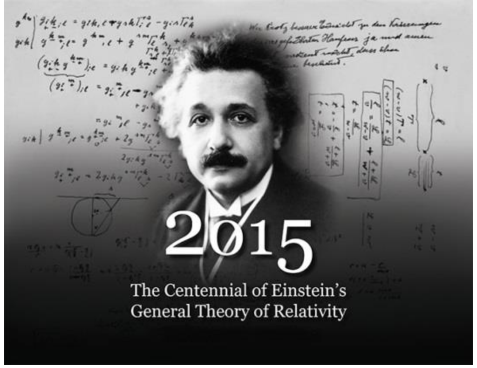
- Add a scalar field φ in the Universe content





General Relativity

- Einstein 1915: **General Relativity**:



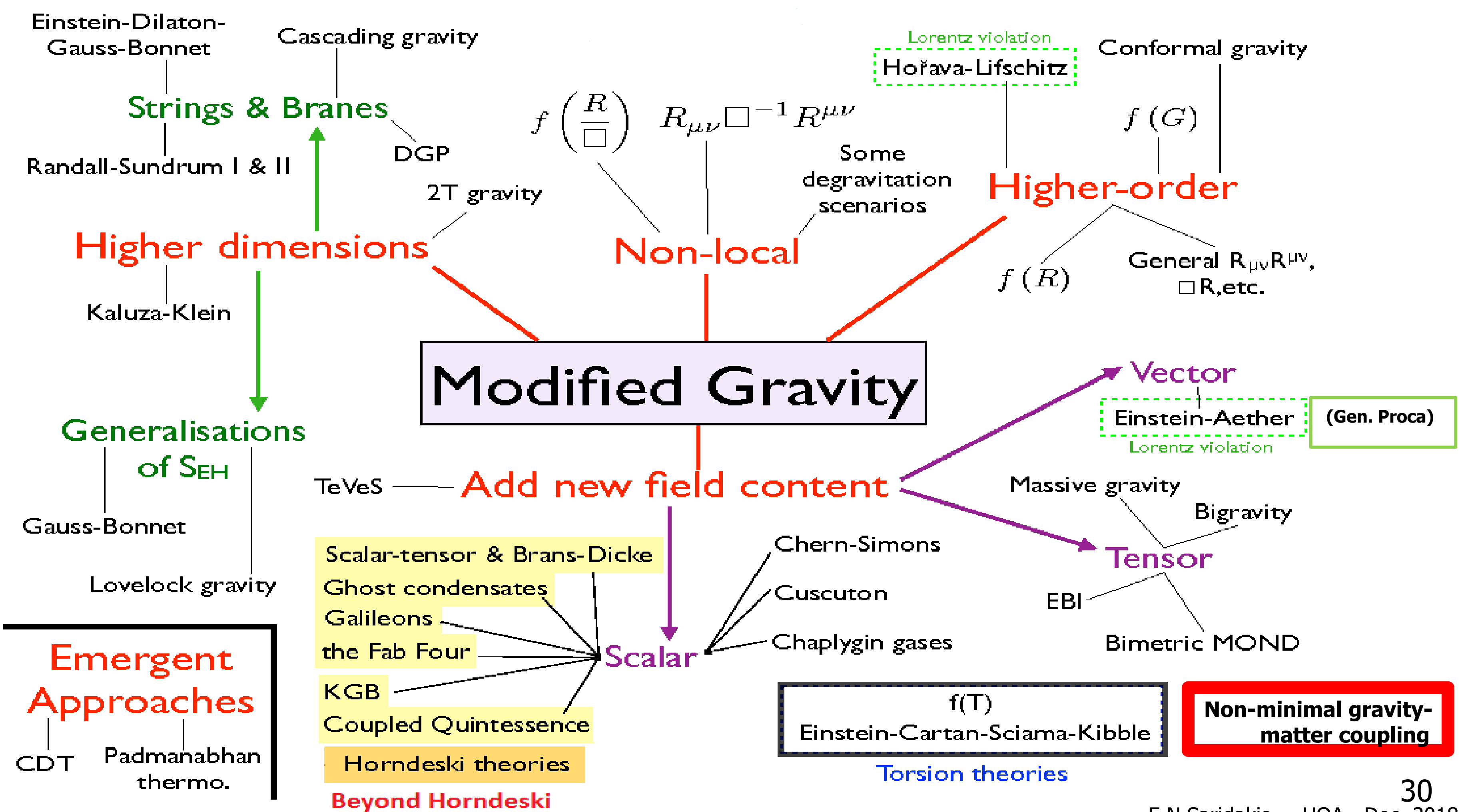
energy-momentum source of spacetime Curvature

$$S=\frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[R-2\Lambda\right]+\int d^4x\, L_m\left(g_{\mu\nu},\psi\right)$$

$$\Rightarrow\quad R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R+g_{\mu\nu}\Lambda=8\pi G\, T_{\mu\nu}$$

with $\quad T^{\mu\nu}\equiv\frac{2}{\sqrt{-g}}\frac{\delta L_m}{\delta g_{\mu\nu}}$

Modified Gravity



Inflation: scalar field

$$\mathrm{L} = \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - \mathrm{V}(\varphi)$$

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)\,, \quad P = \frac{1}{2}\dot{\phi}^2 - V(\phi)\,,$$

$$H^2 = \frac{8\pi}{3m_{\rm pl}^2}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi(\phi) = 0$$

Inflation: scalar field

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$$H^2 = \frac{8\pi}{3m_{\rm pl}^2}\left[\frac{1}{2}\dot\phi^2 + V(\phi)\right]$$

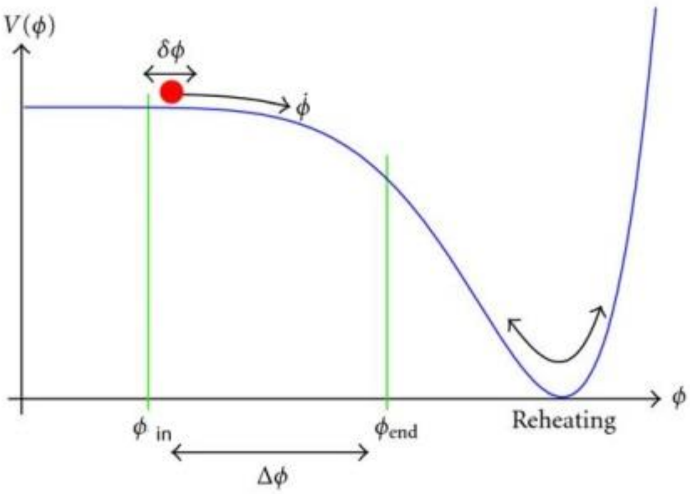
$$\ddot\phi + 3H\dot\phi + V_\phi(\phi) = 0$$

- Slow-roll conditions: $\dot\phi^2/2 \ll V(\phi)$ and $|\ddot\phi| \ll 3H|\dot\phi|$

$$H^2 \simeq \frac{8\pi V(\phi)}{3m_{\rm pl}^2}\,,$$

$$3H\dot\phi \simeq -V_\phi(\phi)$$

$$N \equiv \ln\frac{a_f}{a} = \int_t^{t_f} H\mathrm{d}t \simeq \frac{8\pi}{m_{\rm pl}^2}\int_{\phi_f}^{\phi}\frac{V}{V_\phi}\mathrm{d}\phi$$

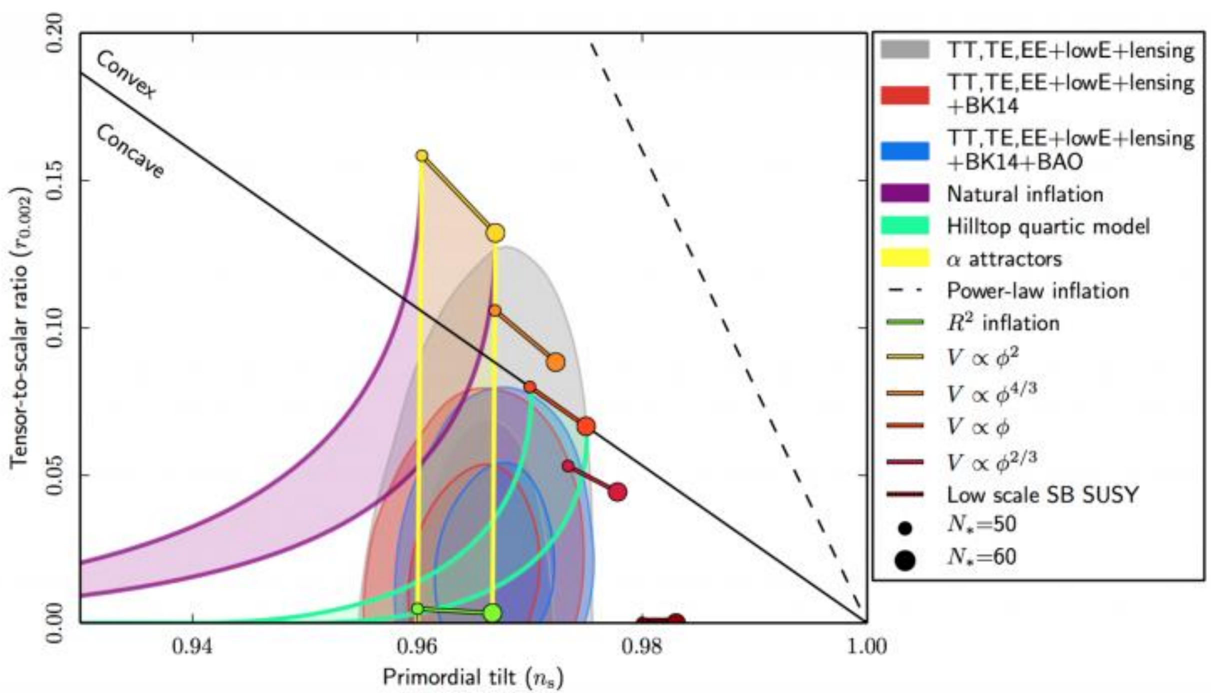


Inflation: scalar field

$$\epsilon = \frac{m_{\rm pl}^2}{16\pi}\left(\frac{V_\phi}{V}\right)^2 , \ \eta = \frac{m_{\rm pl}^2 V_{\phi\phi}}{8\pi V} , \ \xi^2 = \frac{m_{\rm pl}^4 V_\phi V_{\phi\phi\phi}}{64\pi^2 V^2}$$

$$n_s \approx 1 - 6\epsilon + 2\eta$$

$$r \approx 16\epsilon$$



Scalar-Tensor Theories

- Most general 4D scalar-tensor theories having second-order field equations:

$$L_H = \sum_{i=2}^{5} L_i$$

$$L_2[K] = K(\phi, X)$$

$$L_3[G_3] = -G_3(\phi, X)\Diamond\phi$$

$$X = -\partial^\mu\phi\partial_\mu\phi/2$$

$$L_4[G_4] = G_4(\phi, X)R + G_{4,X}\left[(\Diamond\phi)^2 - (\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi)\right]$$

$$L_5[G_5] = G_5(\phi, X)G_{\mu\nu}(\nabla^\mu\nabla^\nu\phi) - \frac{1}{6}G_{5,X}\left[(\Diamond\phi)^3 - 3(\Diamond\phi)(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi) + 2(\nabla^\mu\nabla_\alpha\phi)(\nabla^\alpha\nabla_\beta\phi)(\nabla^\beta\nabla_\mu\phi)\right]$$

[G. Horndeski, Int. J. Theor. Phys. 10]

Horndeski Theories

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$$L_5[G_5] = G_5(\phi, X)G_{\mu\nu}(\nabla^\mu\nabla^\nu\phi) - \frac{1}{6}G_{5,X}\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi) + 2(\nabla^\mu\nabla_\alpha\phi)(\nabla^\alpha\nabla_\beta\phi)(\nabla^\beta\nabla_\mu\phi)\right]$$

[G. Horndeski, Int. J. Theor. Phys. 10]

- Coincides with Generalized Galileon theories

$$\phi \to \phi + c, \;\; \partial_\mu\phi \to \partial_\mu\phi + b_\mu$$

[Nicolis,Rattazzi,Trincherini, PRD 79]

Horndeski Cosmology (background)

- Field Equations: $L.H.S = R.H.S$
- In flat FRW:
- $$2XK_{,X} - K + 6X\dot{\phi}HG_{3,X} - 2XG_{3,\phi} - 6H^2G_4 + 24H^2X(G_{4,X} + XG_{4,XX}) - 12HX\dot{\phi}G_{4,\phi X} - 6H\dot{\phi}G_{4,\phi} + 2H^3X\dot{\phi}(5G_{5,X} + 2XG_{5,XX}) - 6H^2X(3G_{5,\phi} + 2XG_{5,\phi X}) = -\rho_m$$
- $$K - 2X(G_{3,\phi} + \ddot{\phi}G_{3,X}) + 2(3H^2 + 2\dot{H})G_4 - 12H^2XG_{4,X} - 4H\dot{X}G_{4,X} - 8\dot{H}XG_{4,X} - 8HX\dot{X}G_{4,XX} + 2(\ddot{\phi} + 2H\dot{\phi})G_{4,\phi} + 4XG_{4,\phi\phi} + 4X(\ddot{\phi} - 2H\dot{\phi})G_{4,\phi X} - 2X(2H^3\dot{\phi} + 2H\dot{H}\dot{\phi} + 3H^2\ddot{\phi})G_{5,X} - 4H^2X^2\ddot{\phi}G_{5,XX} + 4HX(\dot{X} - HX)G_{5,\phi X} + 2\left[2(\dot{H}X + H\dot{X}) + 3H^2X\right]G_{5,\phi} + 4HX\dot{\phi}G_{5,\phi\phi} = -p_m$$
- $$\frac{1}{a^3}\frac{d}{dt}(a^3J) = P_\phi$$

with $J = \dot{\phi}K_{,X} + 6HXG_{3,X} - 2\dot{\phi}G_{3,\phi} + 6H^2\dot{\phi}(G_{4,X} + 2XG_{4,XX}) - 12HXG_{4,\phi X} + 2H^3X(3G_{5,X} + 2XG_{5,XX}) - 6H^2\dot{\phi}(G_{5,\phi} + XG_{5,\phi X})$

$P_\phi = K_{,\phi} - 2X(G_{3,\phi\phi} + \ddot{\phi}G_{3,\phi X}) + 6(2H^2 + \dot{H})G_{4,\phi} + 6H(\dot{X} + 2HX)G_{4,\phi X} - 6H^2XG_{5,\phi\phi} + 2H^3X\dot{\phi}G_{5,\phi X}$

[De Felice,Tsujikawa JCAP 1202]

Horndeski Cosmology (perturbations)

- Scalar perturbations: $ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)\delta_{ij}dx^i dx^j \quad \Rightarrow L.H.S = R.H.S$
- No-ghost condition: $Q_S \equiv \dfrac{w_1(4w_1w_3 + 9w_2^2)}{3w_2^2} > 0$
- No Laplacian instabilities condition: $c_S^2 \equiv \dfrac{3(2w_1^2w_2H - 4w_2^2w_4 + 4w_1w_2\dot{w}_1 - 2w_1^2\dot{w}_2) - 6w_1^2(\rho_m + p_m)}{w_1(4w_1w_3 + 9w_2^2)} > 0$

with $\quad w_1 \equiv 2(G_4 - 2XG_{4,X}) - 2X(G_{5,X}\dot{\phi}H - G_{5,\phi})$

$$w_2 \equiv -2G_{3,X}X\dot{\phi} + 4G_4H - 16X^2G_{4,XX}H + 4(\dot{\phi}G_{4,\phi X} - 4HG_{4,X})X + 2G_{4,\phi}\dot{\phi}$$
$$+ 8X^2G_{5,\phi X}H + 2HX(6G_{5,\phi} - 5HG_{5,X}\dot{\phi}) - 4G_{5,XX}\dot{\phi}X^2H^2$$

$$w_3 \equiv 3X(K_{,X} + 2XK_{,XX}) + 6X(3X\dot{\phi}HG_{3,XX} - G_{3,\phi X}X - G_{3,\phi} + 6\dot{\phi}HG_{3,X})$$
$$+ 18H(4HX^3G_{4,XXX} - HG_4 - 5X\dot{\phi}G_{4,\phi X} - G_{4,\phi}\dot{\phi} + 7HG_{4,X}X + 16HX^2G_{4,XX} - 2X^2\dot{\phi}G_{4,X\phi X})$$
$$+ 6H^2X(2H\dot{\phi}G_{5,XXX}X^2 - 6X^2G_{5,\phi XX} + 13XH\dot{\phi}G_{5,XX} - 27G_{5,\phi X}X + 15H\dot{\phi}G_{5,X} - 18G_{5,\phi})$$

$$w_4 \equiv 2G_4 - 2XG_{5,\phi} - 2XG_{5,X}\ddot{\phi}$$

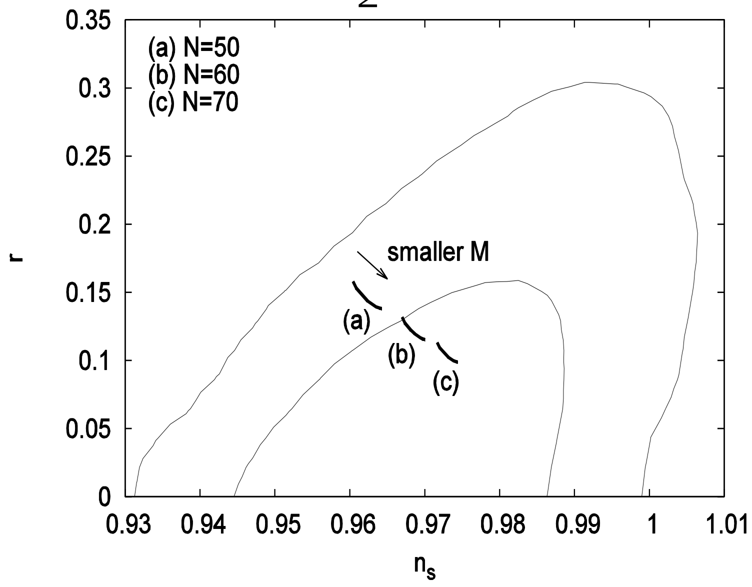
[De Felice,Tsujikawa JCAP 1202]

Inflation in Horndeski Theories

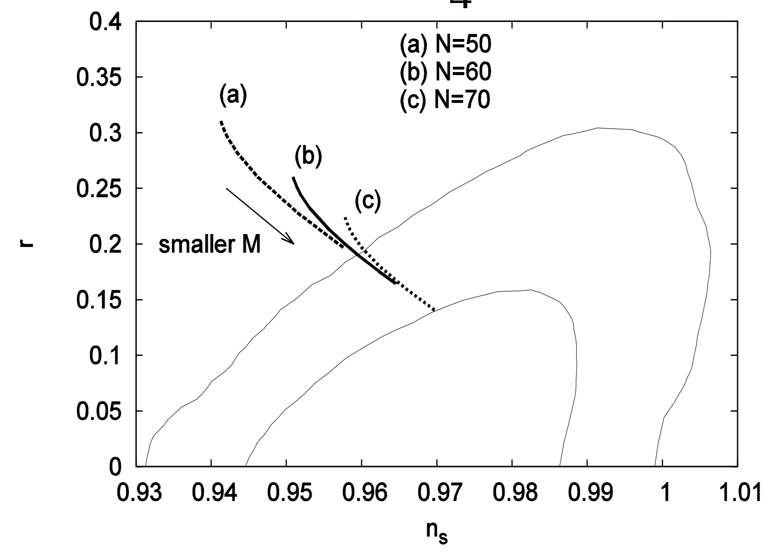
$$K(\phi, X) = X - V(\phi), \; G_3(\phi, X) = \frac{c_3}{M^3} X, \; G_4 = G_5 = 0$$

[Ohashi,Tsujikawa, JCAP 1210]

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$



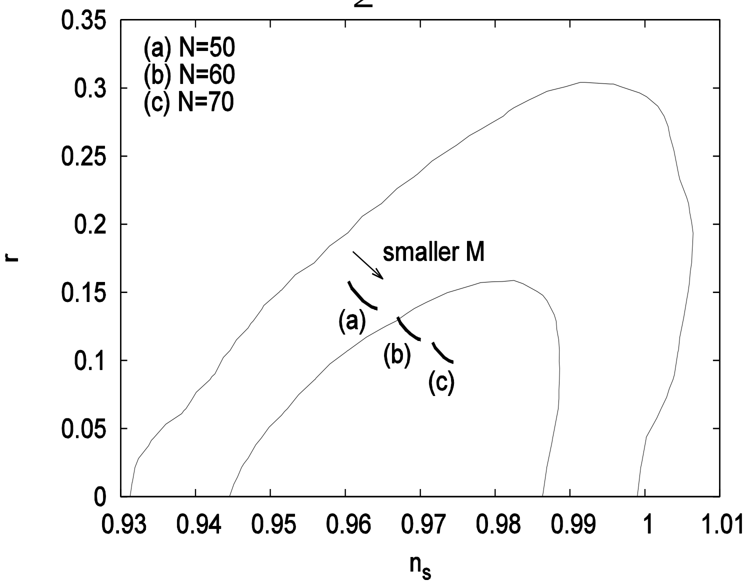
$$V(\phi) = \frac{1}{4} \lambda \phi^4$$



Inflation in Horndeski Theories

- $K(\phi,X)=X-V(\phi),\ G_3(\phi,X)=\frac{c_3}{M^3}X,\ G_4=G_5=0$ [Ohashi,Tsujikawa, JCAP 1210]

$V(\phi)=\frac{1}{2}m^2\phi^2$



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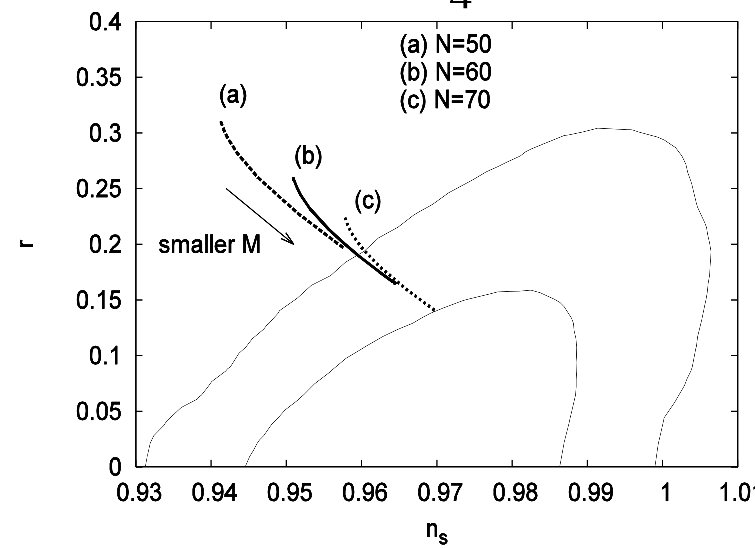


- G-Inflation (Shift-symmetric): $K(\phi,X)=X+\frac{X^2}{2M^3\mu},\ G_3(\phi,X)=\frac{1}{M^3}X,\ G_4=G_5=0$

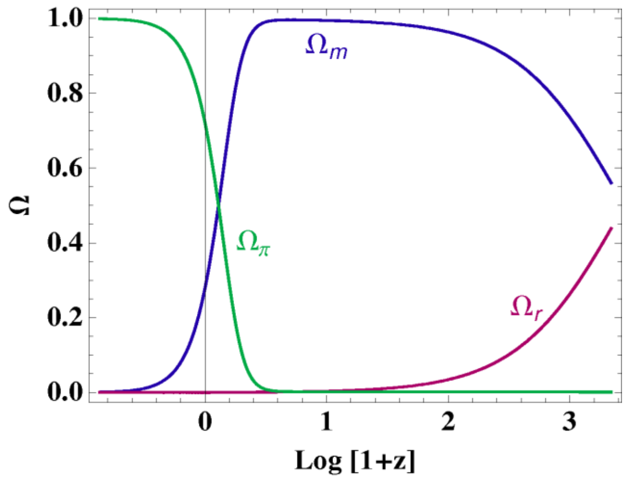
$r\approx 0.17$

[Kobayashi,Yamaguchi,Yokoyama PRL 105] [Banerjee, Saridakis PRD 95]

Dark Energy in Horndeski Theories

- $K(\phi, X) = c_2 X,\; G_3(\phi, X) = c_3,\; G_4 = 1,\; G_5 = c_5$

- Background evolution: Universe thermal history



[Ali,Gannouji,Sami PRD 82] [Leon, Saridakis JCAP 1303]

Dark Energy in Horndeski Theories

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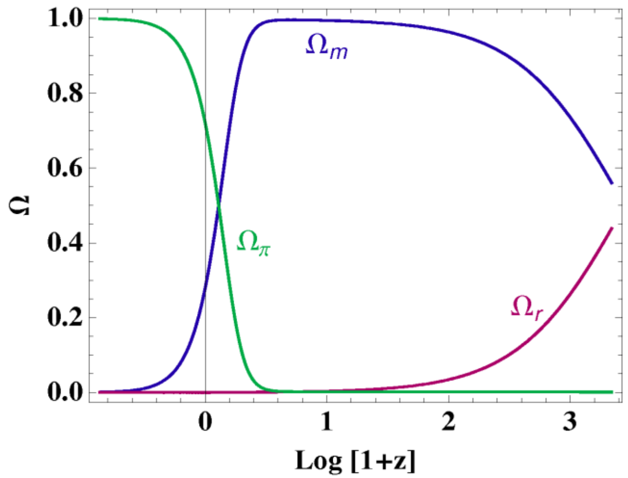
[Leon, Saridakis JCAP 1303]

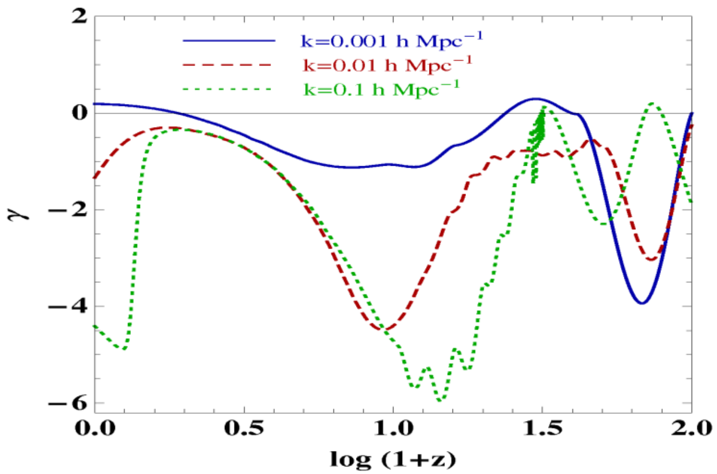


- Perturbations: $\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G_{eff}\rho_m\delta_m$

  with $G_{eff} = G_{eff}(\phi, K, G_3, G_4, G_5)$

- Clustering growth rate: $\frac{d\ln\delta_m}{d\ln a} = \Omega_m^\gamma(a)$

  γ(z): Growth index.



[Ali,Gannouji,Sami PRD 82]

Nonminimal Derivative Coupling – Dark Energy

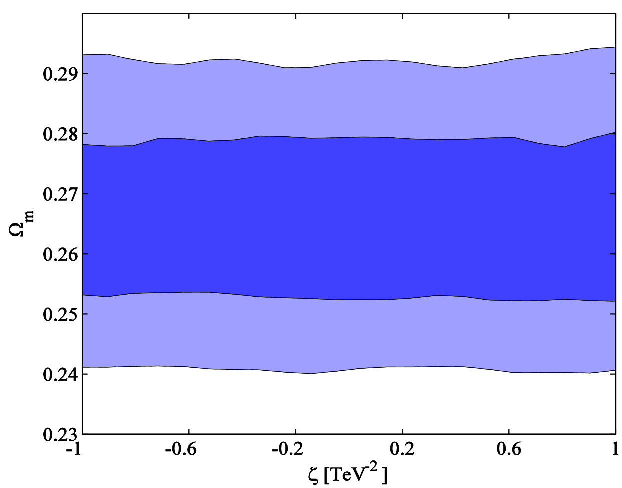
$$S=\int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}R-\frac{1}{2}(g_{\mu\nu}-\zeta G_{\mu\nu})\partial^\mu\phi\partial^\nu\phi-V(\phi)\right]+S_m+S_r$$

- In flat FRW:

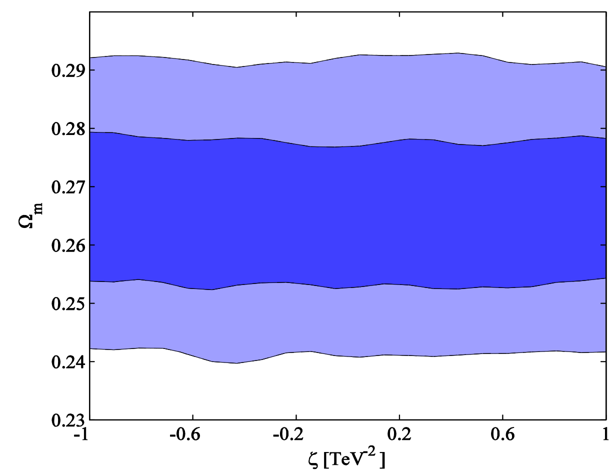
$$H^2=\frac{8\pi G}{3}\left[\frac{\dot\phi^2}{2}\left(1+9\zeta H^2\right)+V(\phi)+\rho_m+\rho_r\right]$$

$$2\dot H+3H^2=-8\pi G\left[\frac{\dot\phi^2}{2}\left[1-\zeta\left(2\dot H+3H^2+\frac{4H\ddot\phi}{\dot\phi}\right)\right]-V(\phi)+p_m+p_r\right]$$

[Saridakis,Suskov PRD 81]



$V(\phi)=V_0e^{\lambda\phi}$



$V(\phi)=V_0\phi^n$

[Dent,Dutta,Saridakis,Xia JCAP 1311]

Dark Matter – Dark Energy Interaction

- Theoretical argument: In principle, since the underlying theory and the microphysics of both dark energy and dark matter is unknown, possible mutual interactions cannot be excluded.

Dark Matter – Dark Energy Interaction

- Theoretical argument: In principle, since the underlying theory and the microphysics of both dark energy and dark matter is unknown, possible mutual interactions cannot be excluded.

- Phenomenological argument: Alleviate the coincidence problem: Why are the DE and DM densities nearly equal today, although they scale independently through the expansion history

[Billyard, Coley, PRD 61] [Mimoso, Nunes, Pavon, PRD 73] [Chen, Gong, Saridakis JCAP 0904]

DM – DE Interaction

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}R\right]+S_\phi+S_{DM}+S_b$$

- Assume that DE and DM are effectively described by perfect fluids.

$$H^2=\frac{8\pi G}{3}(\rho_{DE}+\rho_{DM})$$

$$\dot{H}=-4\pi G(\rho_{DE}+p_{DM})$$

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$$H^2=\frac{8\pi G}{3}(\rho_{DE}+\rho_{DM})$$

$$\dot{H}=-4\pi G(\rho_{DE}+p_{DM})$$

- Equations give only the total conservation, namely

$$\nabla^b T_{ab}^{(tot)}=\nabla^b\left[T_{ab}^{(DE)}+T_{ab}^{(DM)}\right]=0$$

- If we assume DM conservation, i.e $\nabla^b T_{ab}^{(DM)}=0$ then DE is also conserved: $\nabla^b T_{ab}^{(DE)}=0$

$$\Rightarrow\dot{\rho}_{DM}+3H(\rho_{DM}+p_{DM})=0$$
$$\Rightarrow\dot{\rho}_{DE}+3H(\rho_{DE}+p_{DE})=0$$

DM – DE Interaction

- However, it is not forbidden to assume DM – DE interaction by arbitrarily splitting as:

$$\nabla^b T_{ab}^{(DM)} = Q_a$$

$$\nabla^b T_{ab}^{(DE)} = -Q_a$$

with Q_a a phenomenological descriptor of the interaction (positive Q_a corresponds to energy transfer from DE to DM and vice versa).

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- Despite possible pathologies (curvature perturbation blowing up in super-Hubble scales [Valiviita,Majerotto,Maartens, JCAP 0807]) it leads to interesting cosmological behavior.

Phenomenological Models

- I) $Q = Q_0 = 3H(\alpha_{DE}\rho_{DE} + \alpha_{DM}\rho_{DM})$
- II) $Q = Q_0 = \Gamma\rho_{DM}$
- III) $Q = Q_0 = \alpha\kappa^{2n}H^{3-2n}\rho_{_{DM}}^{n}$
- etc…

Phenomenological Models

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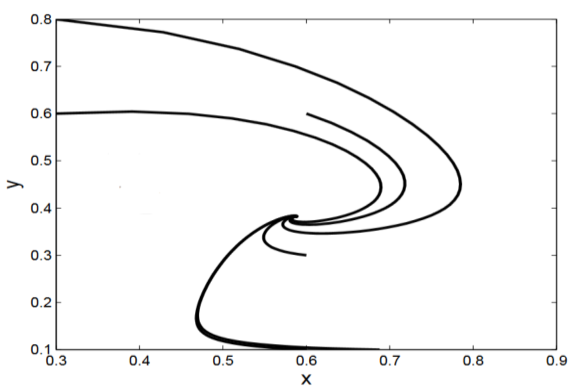
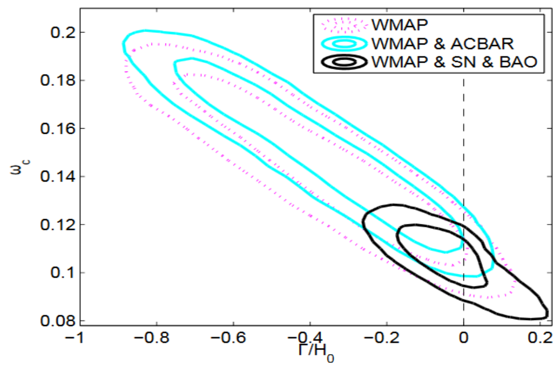
- III) $Q = Q_0 = \alpha\kappa^{2n}H^{3-2n}\rho_{DM}^{n}$
- etc…
- Obtain late time attractors with $R \equiv \rho_{DE} / \rho_{DM} \sim 1$
- 



[Chen, Gong, Saridakis JCAP 0904]

[Valiviita,Majerotto,Maartens, MNRAS 402]

[Caldera-Cabral, Maartens, Urena-Lopez, PRD 79]

Another approach to phenomenological models

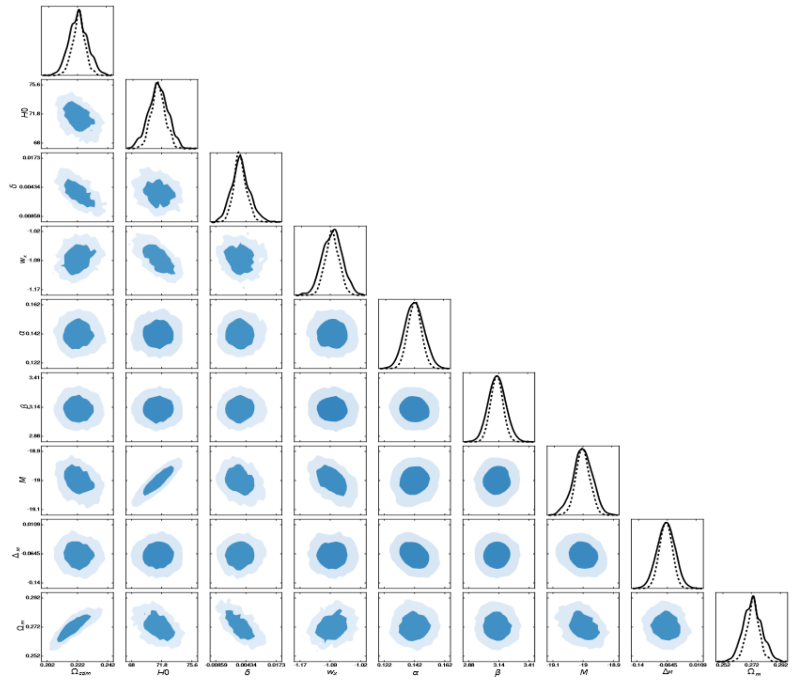
- If Q=0 then $\rho_{DM} = \rho_{DM0}/a^3$. Instead of imposing Q one can parametrize its effect assuming:

$$\rho_{DM} = \rho_{DM0}/a^{3-\delta}$$

(perturbations can also be studied; obtain matter overdensity) [Wang, Meng CQG 22]

Param.	best-fit	mean$\pm\sigma$	95% lower	95% upper
Ω_{cdm0}	0.2246	$0.2229^{+0.0063}_{-0.0069}$	0.2099	0.2365
H_0	71.17	$71.37^{+1.3}_{-1.3}$	68.67	74.01
δ	0.00099	$0.00196^{+0.0038}_{-0.0046}$	-0.00631	0.01085
w	-1.085	$-1.087^{+0.027}_{-0.028}$	-1.139	-1.032
α	0.143	$0.1422^{+0.0065}_{-0.007}$	0.1291	0.1556
β	3.117	$3.126^{+0.079}_{-0.083}$	2.966	3.29
M	-19.04	$-19.04^{+0.041}_{-0.037}$	-19.12	-18.96
Δ_M	-0.0721	$-0.0680^{+0.024}_{-0.023}$	-0.116	-0.0211
Ω_{m0}	0.2746	$0.2729^{+0.0063}_{-0.0069}$	0.2599	0.2865

H0+SNIa+BAO+CMB



- Slight tendency towards interacting DE

δ<0 implies energy flow DM -> DE

[Nunes, Pan, Saridakis PRD 94]

f(R) gravity

$$S=\frac{1}{16\pi G}\int d^4x\sqrt{-g}\,f(R)+S_m\left(g_{\mu\nu},\psi\right)$$

$$f'(R)R_{\mu\nu}-\frac{1}{2}f(R)g_{\mu\nu}-\left[\nabla_\mu\nabla_\mu-g_{\mu\nu}\Diamond\right]f'(R)=8\pi G\,T_{\mu\nu}$$

- Field Equations (metric formalism):

- Conformal transformation: $g_{\mu\nu}\to\tilde{g}_{\mu\nu}=f'(R)g_{\mu\nu}\equiv\phi g_{\mu\nu},\ d\varphi=\sqrt{\frac{2\omega_0+3}{16\pi G}}\frac{d\phi}{\phi}$

$$\Rightarrow_{\omega_0=0}\ S=\int d^4x\sqrt{-\tilde{g}}\left[\frac{\tilde{R}}{16\pi G}-\frac{1}{2}\partial^\alpha\varphi\partial_\alpha\varphi-U(\varphi)\right]+S_m\left(e^{-\sqrt{16\pi G/3}}\tilde{g}_{\mu\nu},\psi\right)\qquad U(\varphi)=\frac{Rf'(R)-f(R)}{16\pi G\left[f'(R)\right]^2}$$

[De Felice, Tsujikawa, Living Rev. Rel. 13]

f(R) cosmology - Inflation

- Firedmann Equations (metric formalism):

$$3FH^2 = \frac{FR-f}{2} - 3H\dot{F} + 8\pi G\,\rho_m$$

$$-2F\dot{H} = \ddot{F} - H\dot{F} + 8\pi G(\rho_m + p_m)$$

$$F(R) \equiv f'(R)$$

$$R = 12H^2 + 6\dot{H}$$

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- Inflation: e.g. Starobinsky inflation

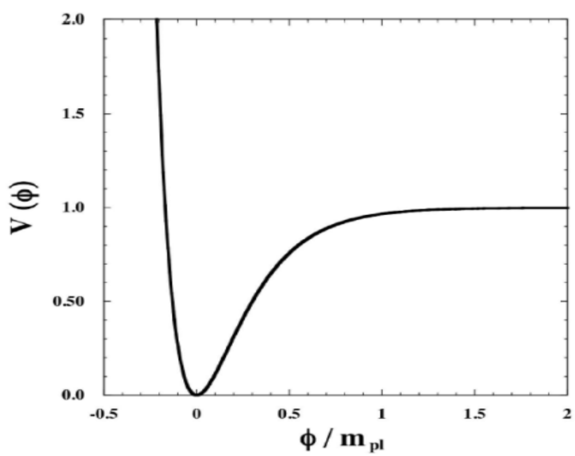
$$f(R) = R + \frac{R^2}{6M^2}$$

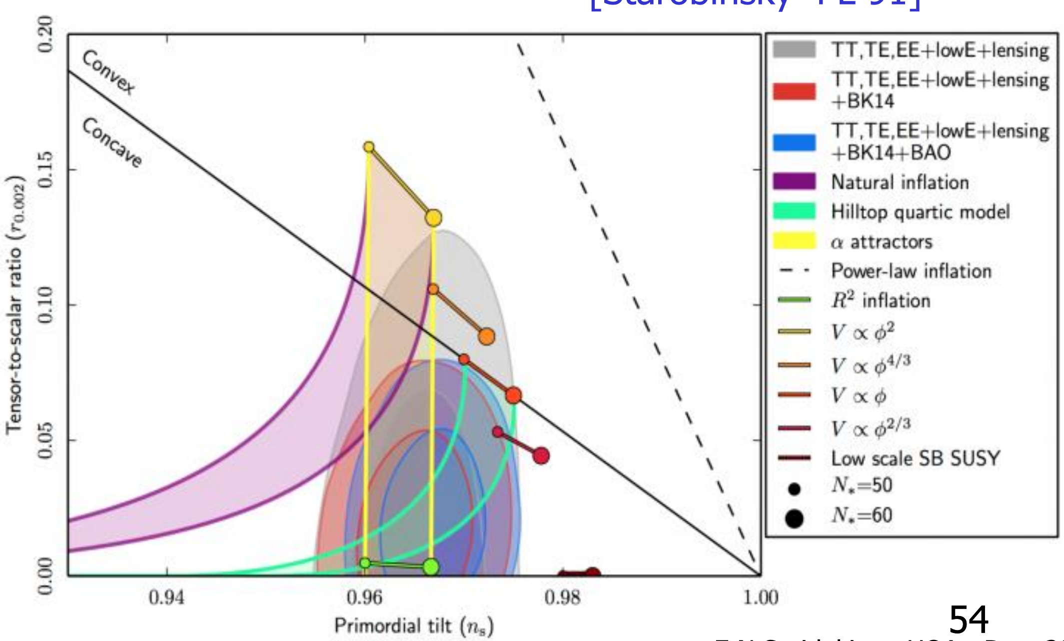
$$\Rightarrow V(\phi) = \frac{3M^2}{32\pi G}\left(1 - e^{-\sqrt{2/3 8\pi G}\phi}\right)$$

[Starobinsky PL 91]

$$H \approx H_i - \frac{M^2}{6}(t - t_i)$$

$$T_{reh} \le 3\times10^{17} g_*^{1/4}\left(\frac{M}{m_{pl}}\right)^{3/2} GeV \qquad M \approx 3\times10^{13}\ GeV$$





f(R) cosmology – Dark energy

$$8\pi G\,\rho_{DE} = \frac{FR - f}{2} - 3H\dot{F} + 3H^2(1-F)$$

$$8\pi G\,p_{DE} = \ddot{F} + 2H\dot{F} - \frac{FR - f}{2} - \left(3H^2 + 2\dot{H}\right)(1-F)$$

for viable: $f_{,R} > 0,\ f_{,RR} > 0,\ for\ R \geq R_0 (> 0)$

[Starobinsky PLB 91]

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[Starobinsky PLB 91]

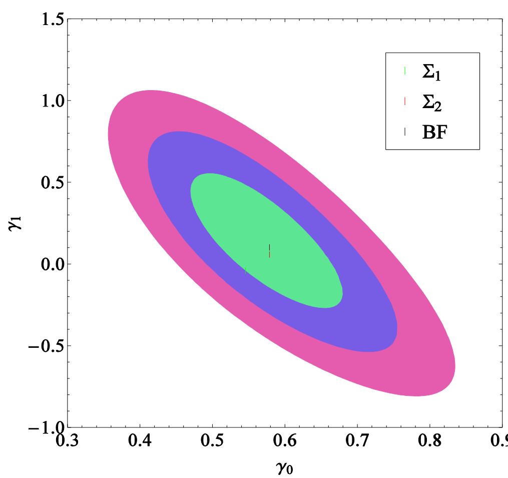
model	$f(R)$	Constant parameters
(i) Hu-Sawicki	$R - \frac{c_1 R_{\rm HS}(R/R_{\rm HS})^p}{c_2 (R/R_{\rm HS})^p + 1}$	$c_1,\ c_2,\ p(>0), R_{\rm HS}(>0)$
(ii) Starobinsky	$R + \lambda R_{\rm S}\left[\left(1+\frac{R^2}{R_{\rm S}^2}\right)^{-n} - 1\right]$	$\lambda(>0),\ n(>0),\ R_{\rm S}$
(iii) Tsujikawa	$R - \mu R_{\rm T}\tanh\left(\frac{R}{R_{\rm T}}\right)$	$\mu(>0),\ R_{\rm T}(>0)$
(iv) Exponential	$R - \beta R_{\rm E}\left(1 - e^{-R/R_{\rm E}}\right)$	$\beta,\ R_{\rm E}$

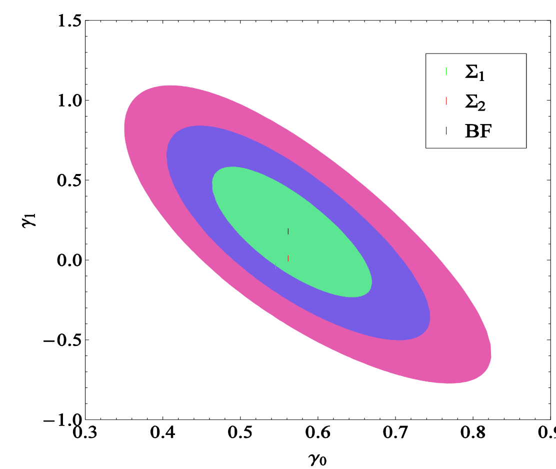
[Bamba,Geng,Lee JCAP 1011]

- $$\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G_{eff}\,\rho_m \delta_m$$

$$G_{eff} = \frac{G}{f'}\,\frac{1 + 4\frac{k^2}{a^2}\frac{f''}{f'}}{1 + 3\frac{k^2}{a^2}\frac{f''}{f'}}$$

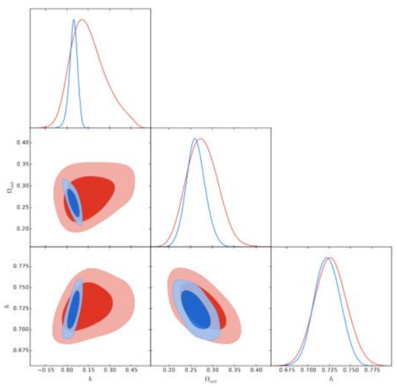
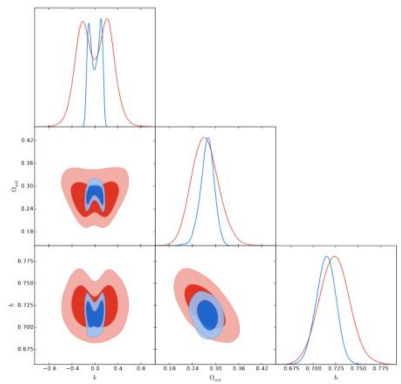
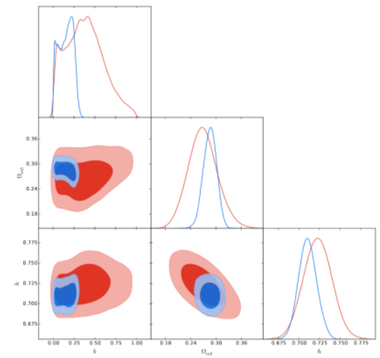
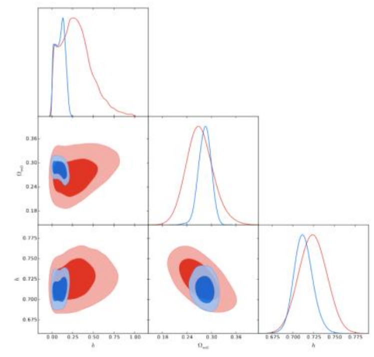
$$\frac{d\ln\delta_m}{d\ln a} = \Omega_m^{\gamma}(a)$$





[Basilakos,Nesseris,Perivolaropoulos PRD 87]

f(R) cosmology – Dark energy

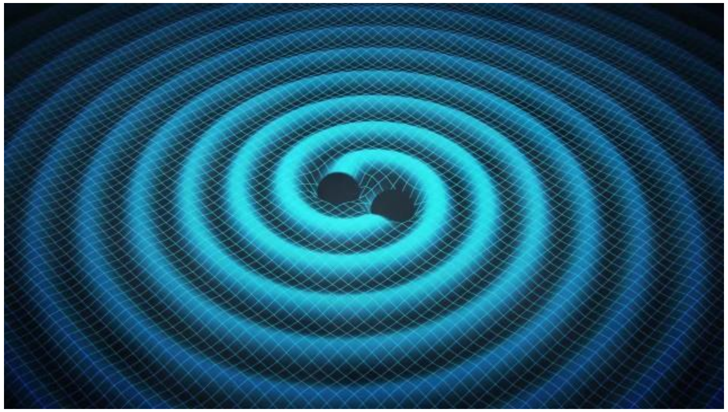
Models	CC+ H_0				JLA + BAO + CC + H_0			
	AIC	ΔAIC	BIC	ΔBIC	AIC	ΔAIC	BIC	ΔBIC
ΛCDM Model	28.205	0	36.809	0	721.084	0	749.017	0
Hu-Sawicki Model	28.744	0.539	38.782	1.973	720.840	−0.244	753.428	4.411
Starobinsky Model	29.096	0.891	39.134	2.325	721.726	0.642	754.314	5.297
Tsujikawa Model	29.407	1.202	39.445	2.636	722.966	1.882	755.554	6.537
Exponential Model	29.310	1.105	39.347	2.538	722.548	1.464	755.136	6.119

[Nunes, Pan, Saridakis, Abreu JCAP 1701]

Gravitational waves

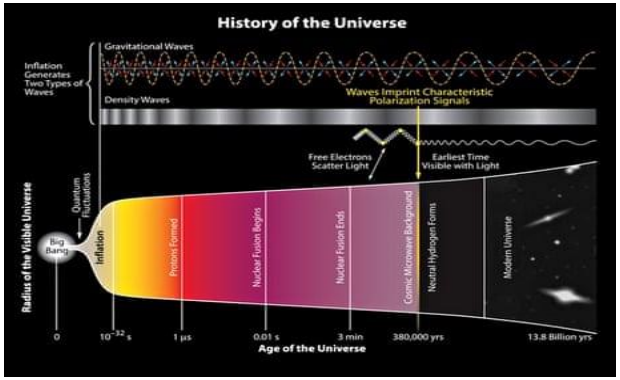
- The GWs are the tensor perturbations of the metric. Predicted in 1915, first observed in 2015. First astronomical observation ever, not related to E/M.

- GWs from mergers:



[Abbott et al, LIGO Virgo PRL 116]

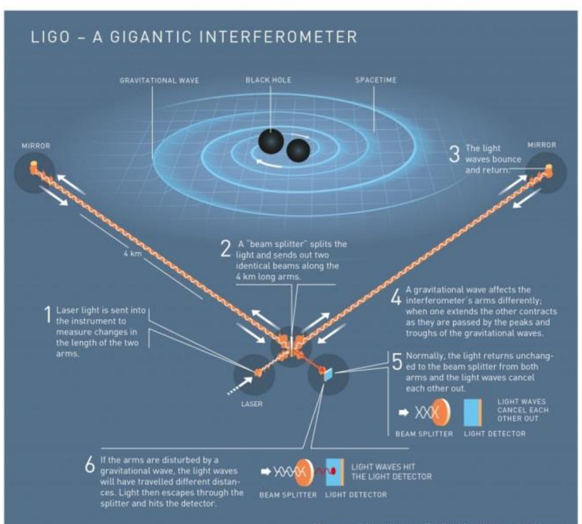
- Primordial GWs:

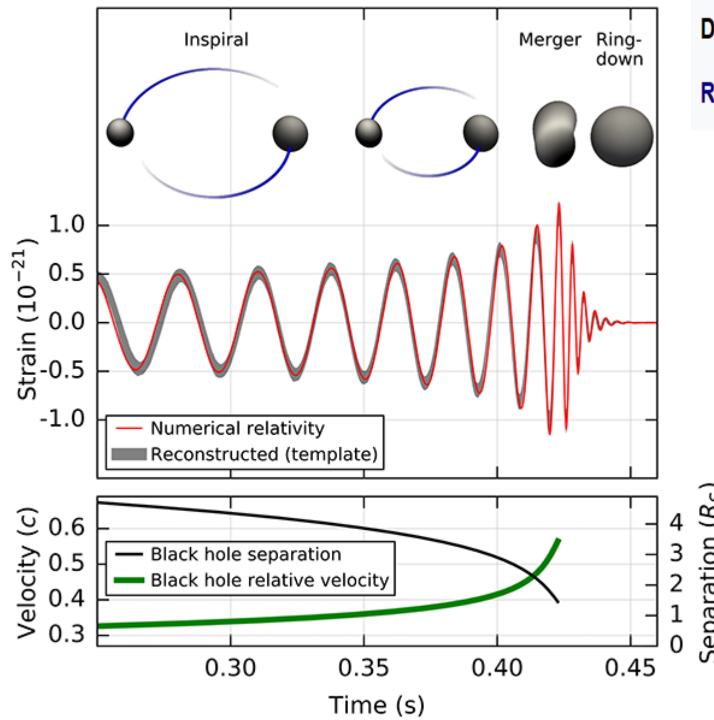


Gravitational waves

- GW150914: Two black holes with 36^{+5}_{-4} M⊙ and 29^{+4}_{-4} M⊙, resulting in a 62^{+4}_{-4} M⊙ black hole

Louisiana.
Washington
4km
10^{-18}m





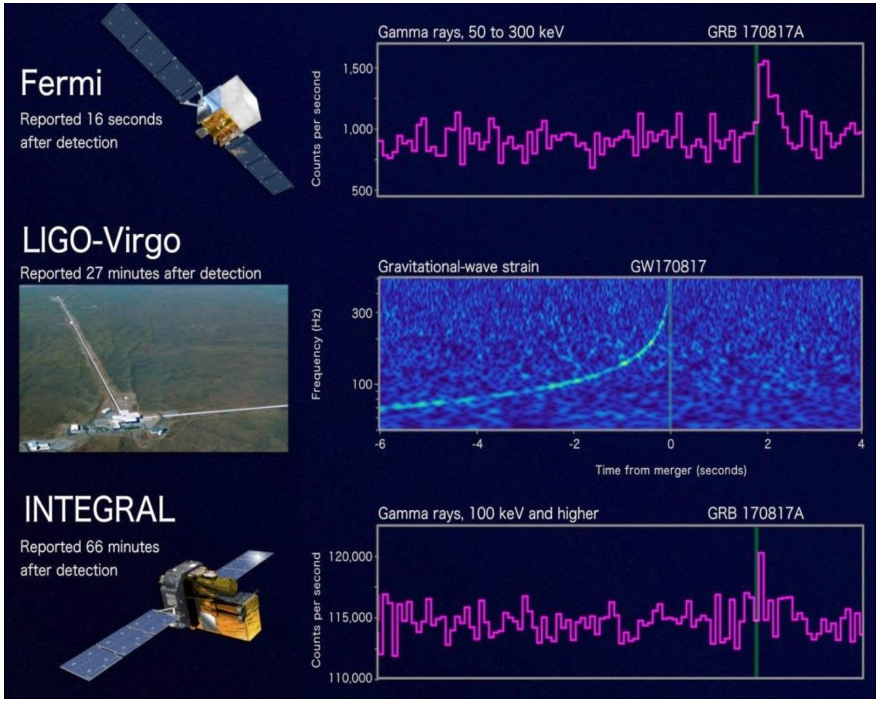
Distance	410^{+160}_{-180} Mpc
Redshift	$0.093^{+0.030}_{-0.036}$

[Abbott et al, LIGO Virgo PRL 116]

2017 Nobel Price in Physics

Gravitational waves

- GW170817: Two neutron stars, distance 40 Mpc, redshift 0.0099
- GRB170817A: The Electromagnetic counterpart.



[Goldstein et al, Fermi Gamma Ray Burst Monitor Astrophys.J 848]

[Abbott et al, LIGO Virgo PRL 119]

- The era of multi-messenger astronomy begins!

Gravitational waves

- In case of GWs from black hole mergers we know their properties at the moment of detection, and their direction (in case of three detectors). Assuming GR and ΛCDM we can extract their speed, distance, and properties at the moment of emission.

Gravitational waves

- In case of GWs from black hole mergers we know their properties at the moment of detection, and their direction (in case of three detectors). Assuming GR and ΛCDM we can extract their speed, distance, and properties at the moment of emission.

- In case of GWs from neutron star mergers, and their E/M counterpart, we know their properties at the moment of detection and their direction, but using the implied physics from the E/M information we can extract their speed, distance and properties at the moment of emission, independently of the underlying gravitational theory and cosmological scenario.

- Great tool for testing General Relativity and cosmological scenarios!

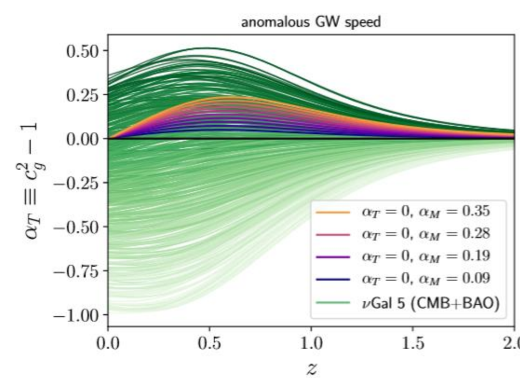
Gravitational waves

- An immediate result: The speed of GWs is equal to the speed of light!

  GW170817 time delay $1.74 \pm 0.05\text{s}$ constrains: $-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}$

- Excludes a large number of theories that were consistent with other data!

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity	quartic/quintic Galileons [13, 14]
	quintessence/k-essence [46]	Fab Four [15]
	Brans-Dicke/$f(R)$ [47, 48]	de Sitter Horndeski [49]
	Kinetic Gravity Braiding [50]	$G_{\mu\nu}\phi^\mu\phi^\nu$ [51], $f(\phi)$·Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17]	quartic/quintic GLPV [18]
	Disformal Tuning (21)	quadratic DHOST [20] with $A_1 \neq 0$
	quadratic DHOST with $A_1 = 0$	cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817



[Ezquiaga, Zumalacarregui PRL 119]

Gravitational waves

- For tensor perturbations:

$$g_{00} = -1\,, \quad g_{0i} = 0\,,$$
$$g_{ij} = a^2\left(\delta_{ij} + h_{ij} + \frac{1}{2}h_{ik}h_{kj}\right)$$

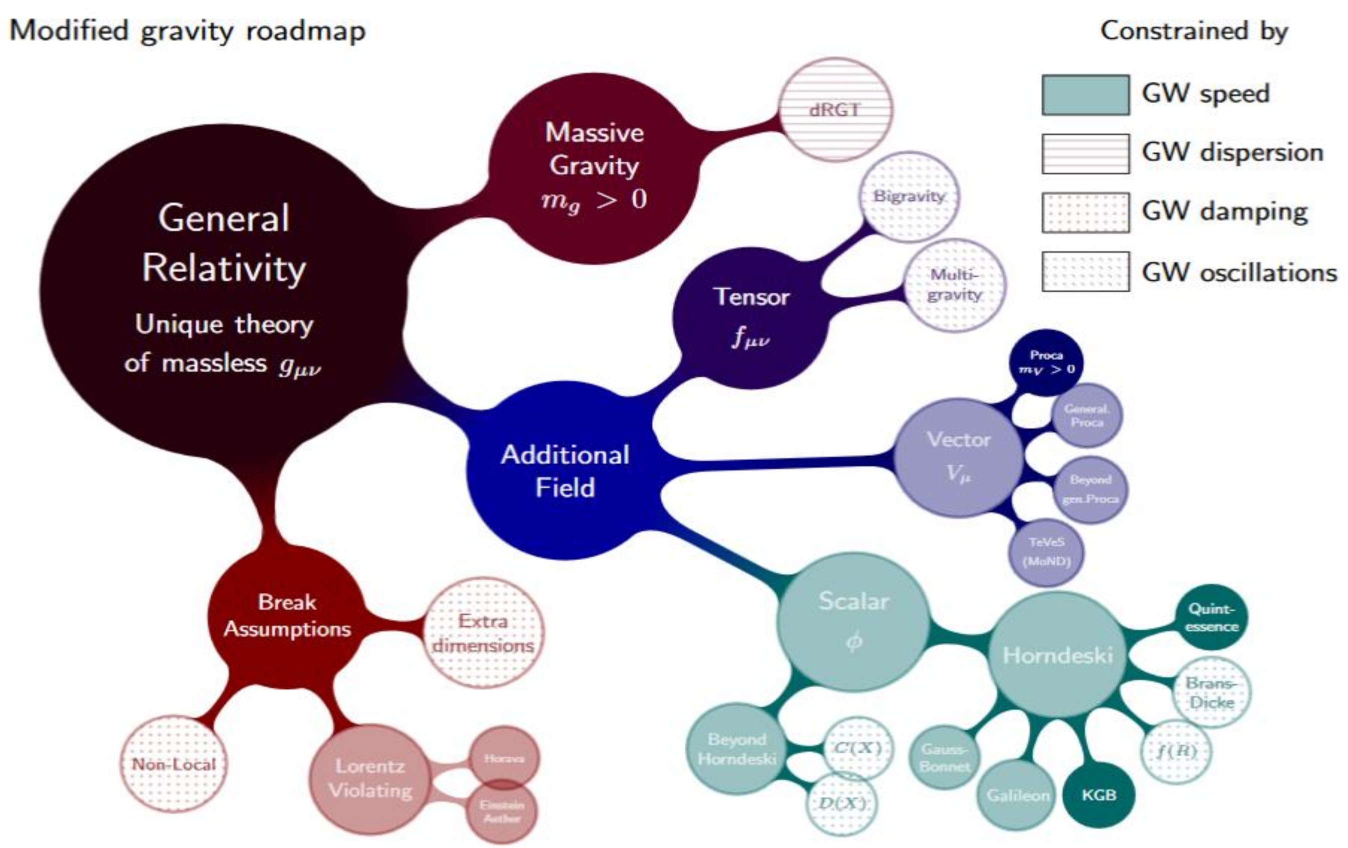
$$\ddot{h}_{ij} + (3+\alpha_M)\dot{h}_{ij} + (1+\alpha_T)\frac{k^2}{a^2}h_{ij} = 0$$

$$\alpha_M = \frac{d\log(M_*^2)}{d\log a} \qquad\qquad c_g^2 = (1+\alpha_T)$$

- $$h_{\rm GW} \sim h_{\rm GR} \underbrace{e^{-\frac{1}{2}\int \nu\mathcal{H}d\eta}}_{\text{Affects amplitude}} \underbrace{e^{ik\int(\alpha_T + a^2m^2/k^2)^{1/2}d\eta}}_{\text{Affects phase}}$$

[Ezquiaga, Zumalacarregui 1807.09241]

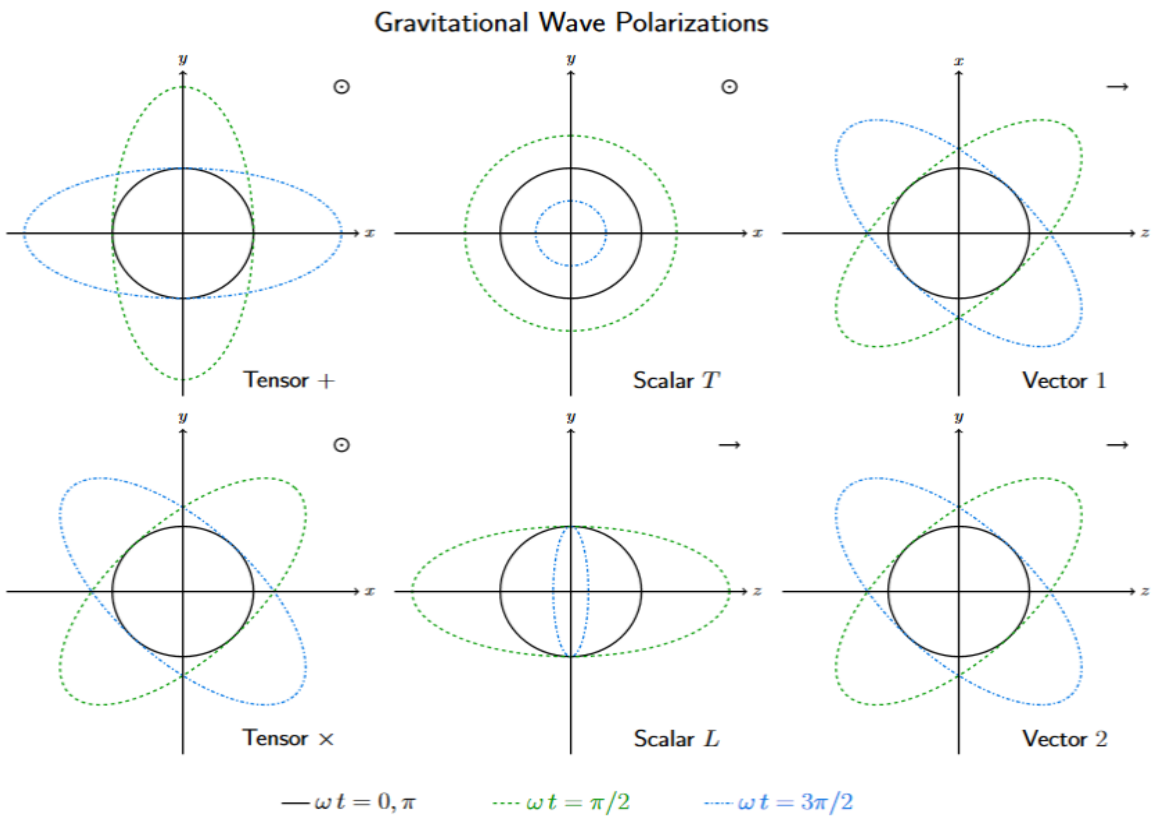
Gravitational waves



[Ezquiaga, Zumalacarregui 1807.09241]

Gravitational waves

- Polarizations:

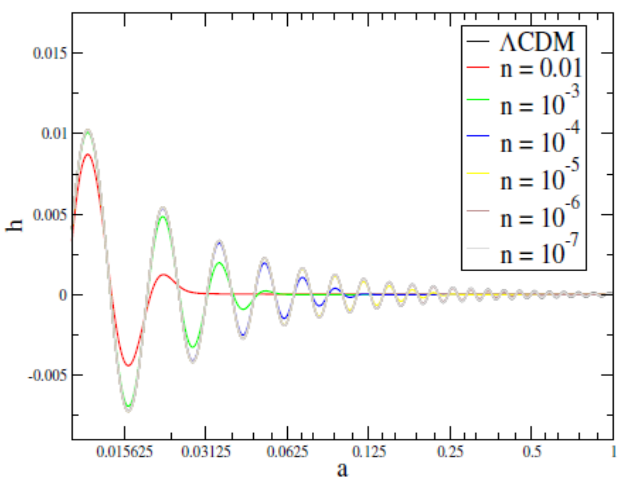


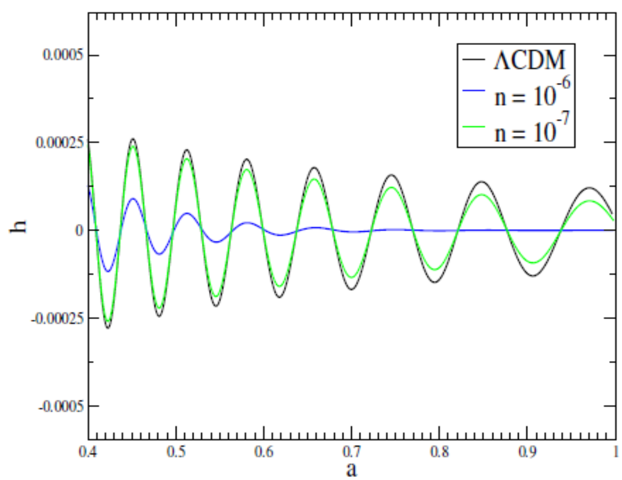
[Ezquiaga, Zumalacarregui 1807.09241]

Gravitational waves

- Testing General Relativity, modified gravities, and various cosmological scenarios.
- The GWs properties at emission and detection are determined by them.

- Examples: f(T), f(R), f(Q), etc





$$h^{(1)}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 2\gamma_1^{(1)1} & {B_1}^2 \exp(ip_\mu x^\mu) & 0 \\ 0 & {B_1}^2 \exp(ip_\mu x^\mu) & -2\gamma_1^{(1)1} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

[Cai, Li, Saridakis, Xue PRD97]

[Farrugia, Said, Gakis, Saridakis, PRD97]

[Soudi, Farrugia, Gakis, Said, Saridakis, 1810.08220]

[Nunes, Pan, Saridakis, PRD98]

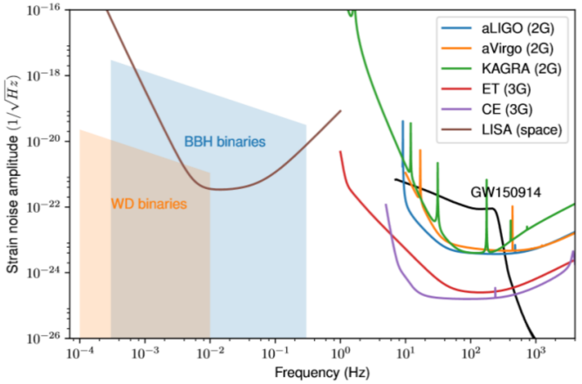
Conclusions

- i) The Standard Model of Cosmology may ask for new physics, definitely for inflation and dark matter, probably for dark energy.

- ii) We can modify the Universe content, or/and the gravitational theory.

- iii) We use various observational data (SnIa, CMB, BAO, H(z), LSS etc) in order to constrain the proposed theories.

- iv) The advancing gravitational wave astronomy, and especially multi-messenger astronomy offers a novel tool to test General Relativity and cosmological scenarios in great accuracy.



- v) A new era has begun!

Outlook

- A huge project is ahead for the community:
- i) Calculate the exact form of GWs created from mergers in various gravitational theories (needs numerical gravity).
- ii) Calculate the propagation of these GWs from emission to detection for various cosmological scenarios.
- iii) Use multi-messenger data to test General Relativity, break degeneracies and constrain or exclude the various theories.
- iv) Elaborate also the creation and possible detection of primordial GWs.
- v) For f(T) gravity, f(R,G), running vacuum, higher-order theories, entropic gravity etc, currently under investigation

  [Saridakis, Assimakis, Erices, Gakis, Palikaris, Theodosiou]
- vi) Get prepared for the huge flow of data that will come!

- “There are the ones that invent occult fluids to understand the Laws of Nature. They come to conclusions, but they now run out into dreams and chimeras neglecting the true constitutions of the things...
  However there are those that from the simplest observation of Nature, they reproduce New Forces”…

From the Preface of PRINCIPIA (II edition) 1687 by Isaac Newton, written by Mr. Roger Cotes.

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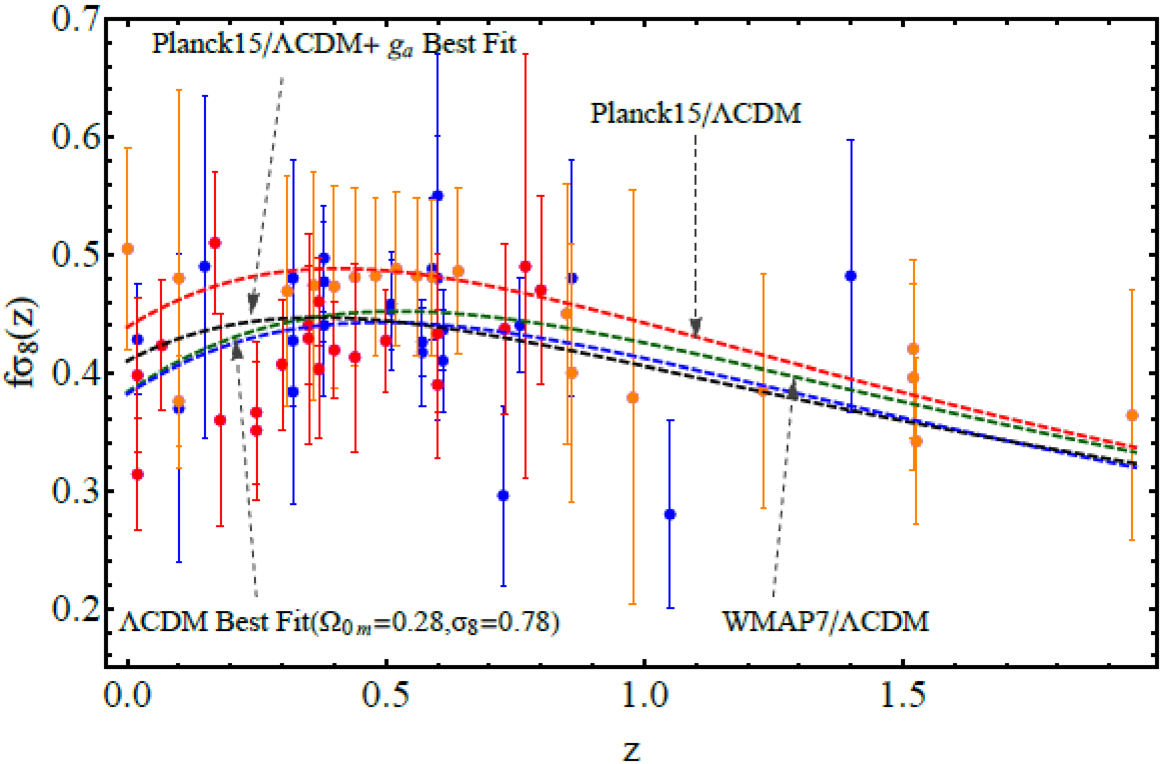
THANK YOU!

Tension1 – fσ8

- Tension between the data and Planck/ΛCDM. The data indicate a lack of "gravitational power" in structures on intermediate-small cosmological scales.

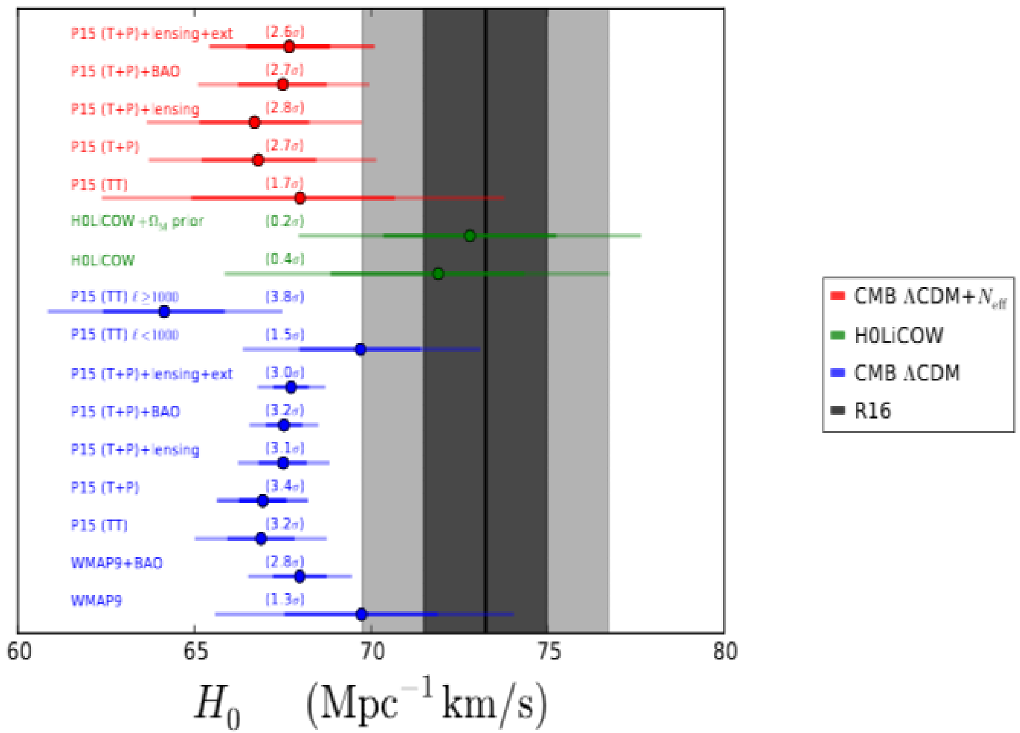
Parameter	Planck15/ΛCDM [12]	WMAP7/ΛCDM [45]
$\Omega_b h^2$	0.02225 ± 0.00016	0.02258 ± 0.00057
$\Omega_c h^2$	0.1198 ± 0.0015	0.1109 ± 0.0056
n_s	0.9645 ± 0.0049	0.963 ± 0.014
H_0	67.27 ± 0.66	71.0 ± 2.5
Ω_{0m}	0.3156 ± 0.0091	0.266 ± 0.025
w	-1	-1
σ_8	0.831 ± 0.013	0.801 ± 0.030



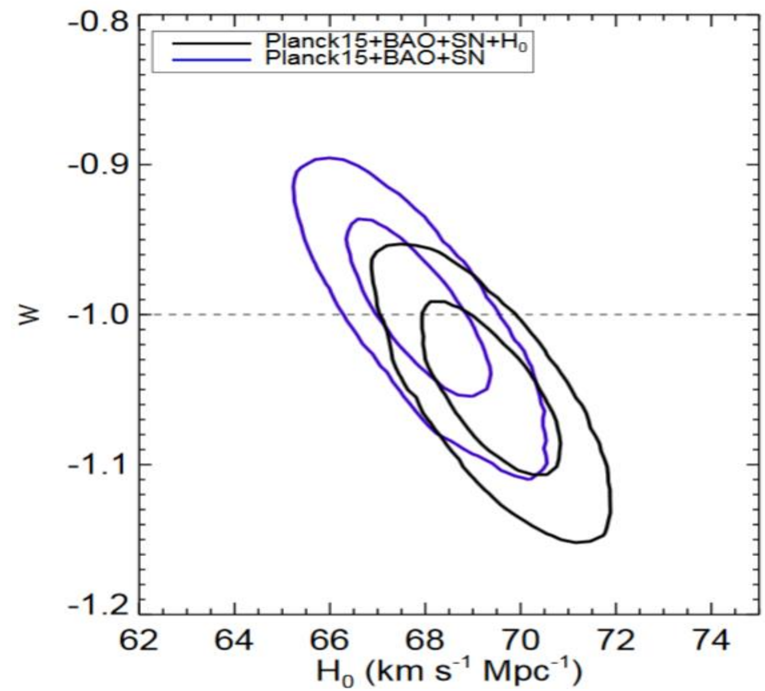
[Kazantzidis, Perivolaropoulos, PRD97]

Tension2 – H0

- Tension between the data (direct measurements) and Planck/ΛCDM (indirect measurements). The data indicate a lack of “gravitational power”.



[Bernal, Verde, Riess, JCAP1610]



[Riess et al, Astrophys.J 826]