Understanding the dynamical nature of late-time cosmic acceleration:

Dark Energy & f(T) Gravity

蔡一夫 Yi-Fu Cai

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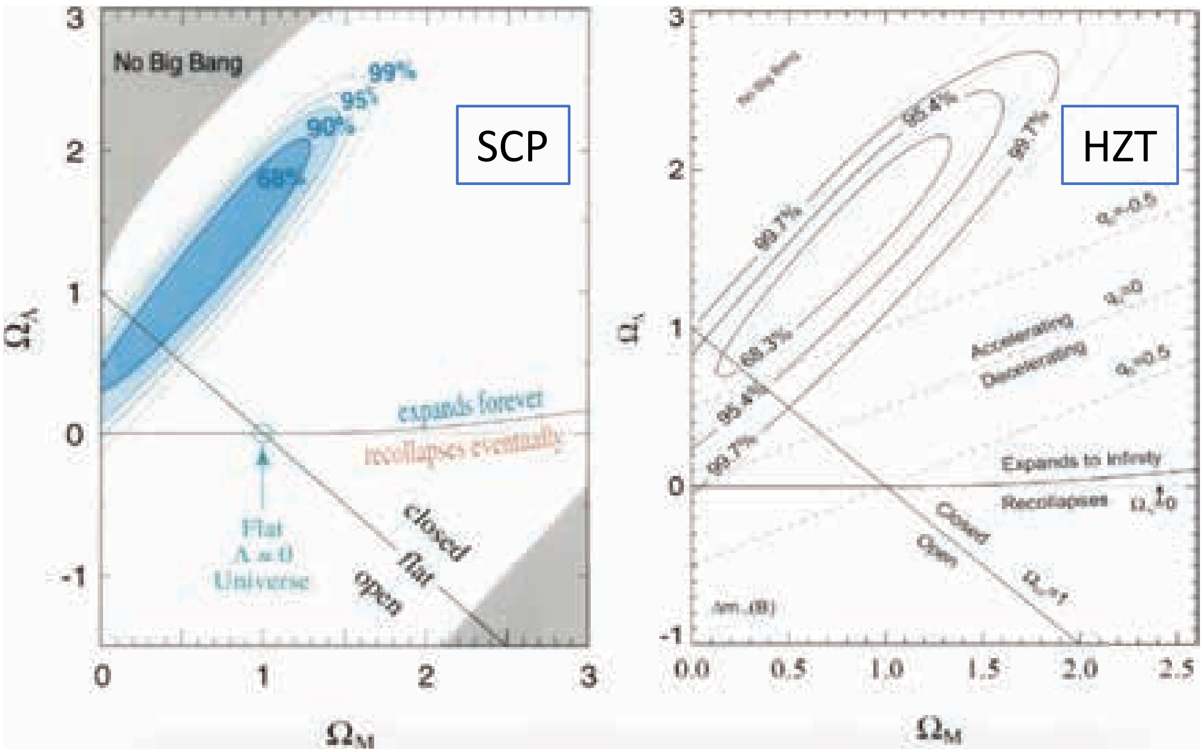
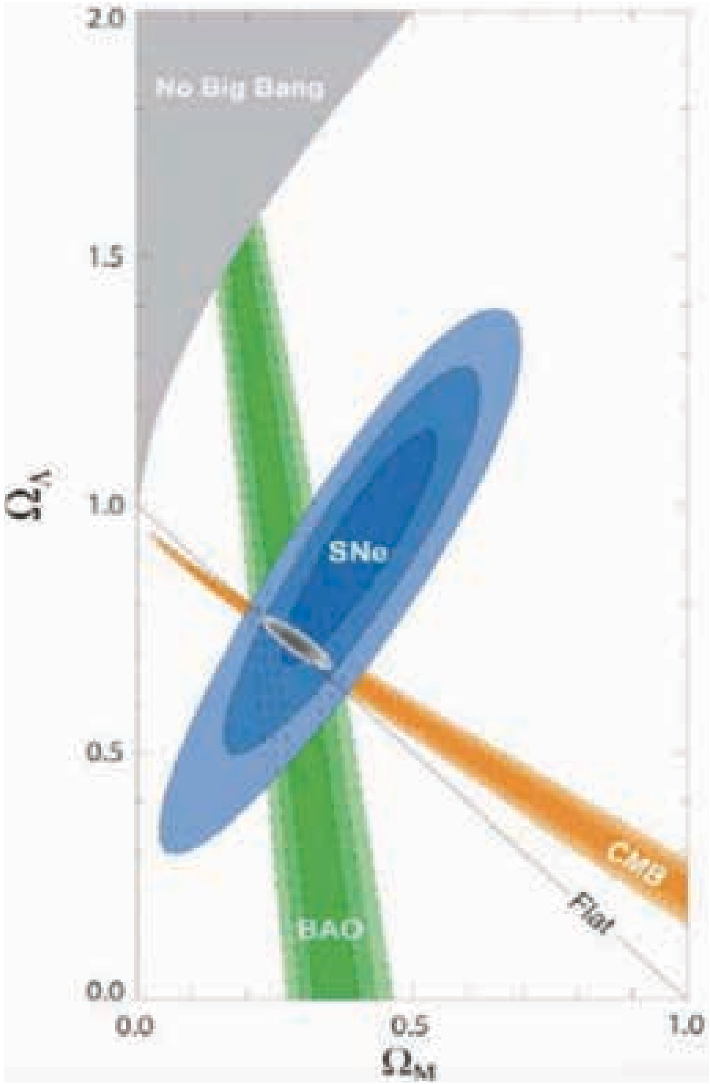
Faculty of Physics, University of Warsaw

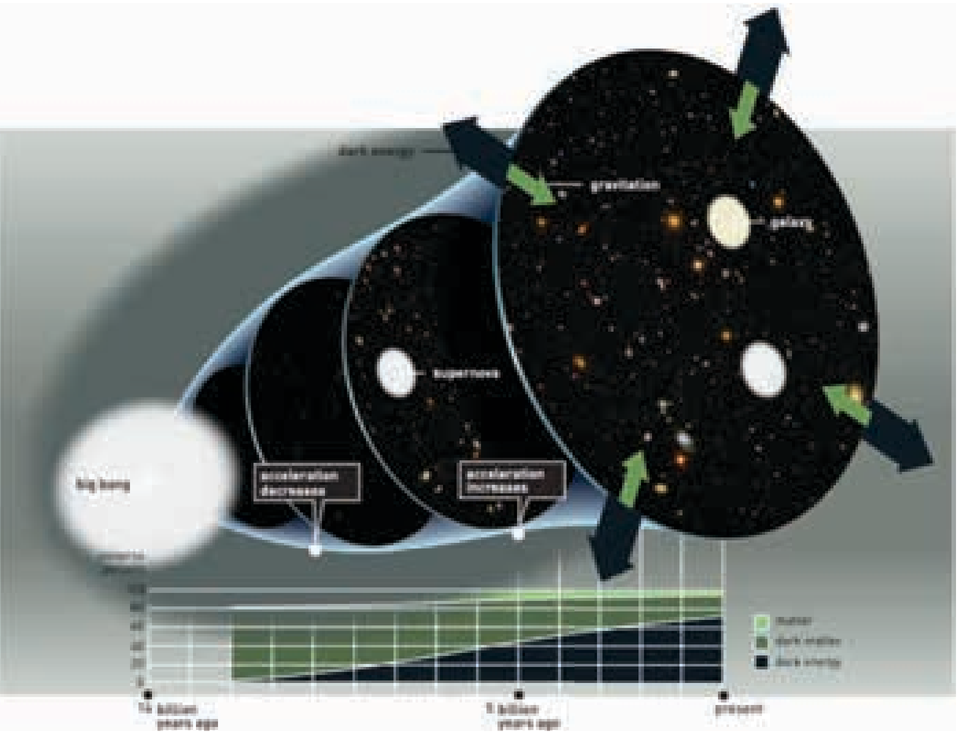
中国科学技术大学天文学系
Department of Astronomy, University of Science and Technology of China

A story begins at 1998
It is about our Universe





In a language of human beings, i.e.
our Universe is under the accelerating expansion

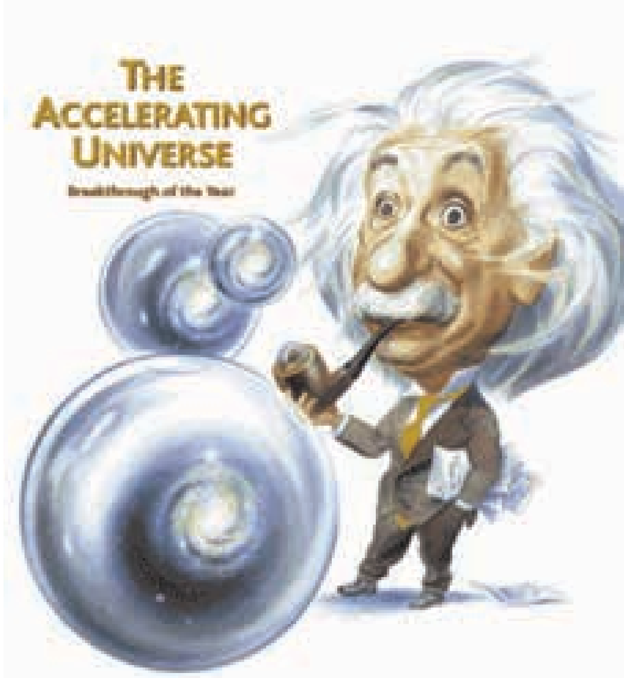


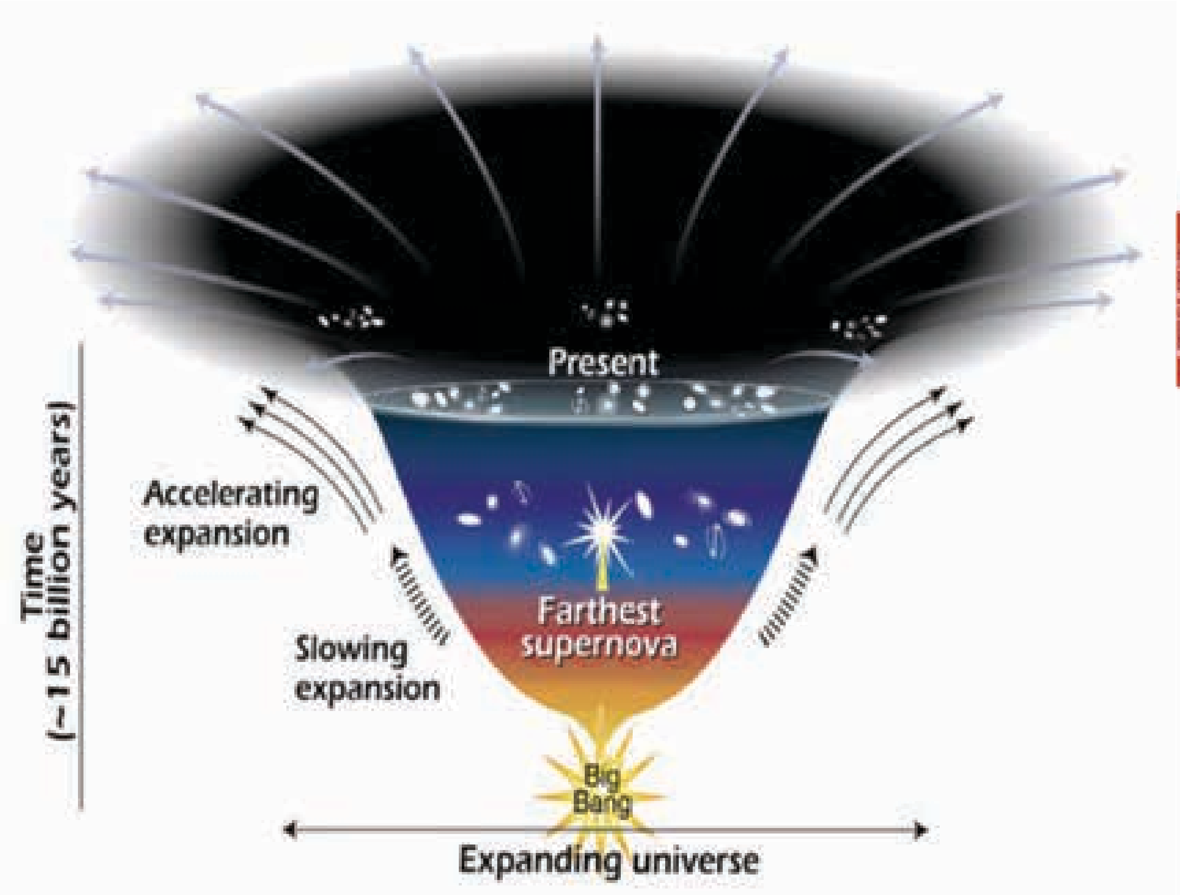
The type-Ia supernovae produces consistent peak luminosity because of the uniform mass of white dwarfs that explode via the accretion mechanism. These explosions can be used as standard candles to measure the distance to their host galaxies because the visual magnitude of the supernovae depends primarily on the distance.

Who cares?

At least for cosmologists who picked up the beautiful mistake of cosmological constant by Einstein;

And perhaps the following three persons …






WHAT DON'T WE KNOW?

Special Section

What Is the Universe Made Of

The Nobel Prize in Physics 2011

© The Nobel Foundation. Photo: U. Montan

Saul Perlmutter

Prize share: 1/2

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Brian P. Schmidt

Prize share: 1/4

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Adam G. Riess

Prize share: 1/4

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

What can drive the late-time cosmic acceleration?

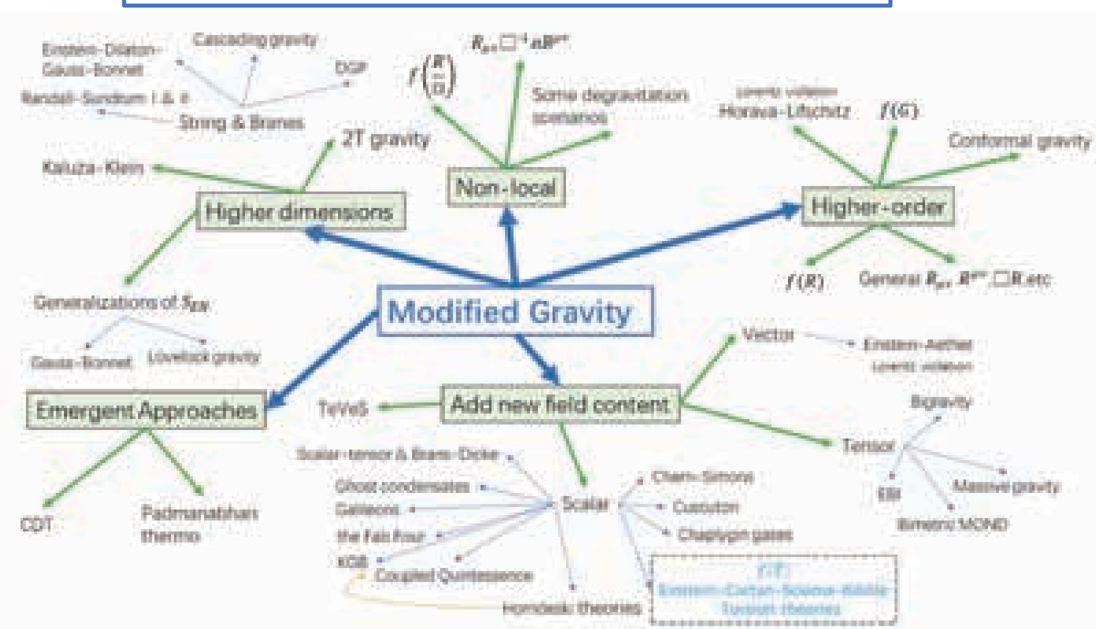
According to Aristotle, anything can't be explained by air, fire, soil, water, it must be quintessence

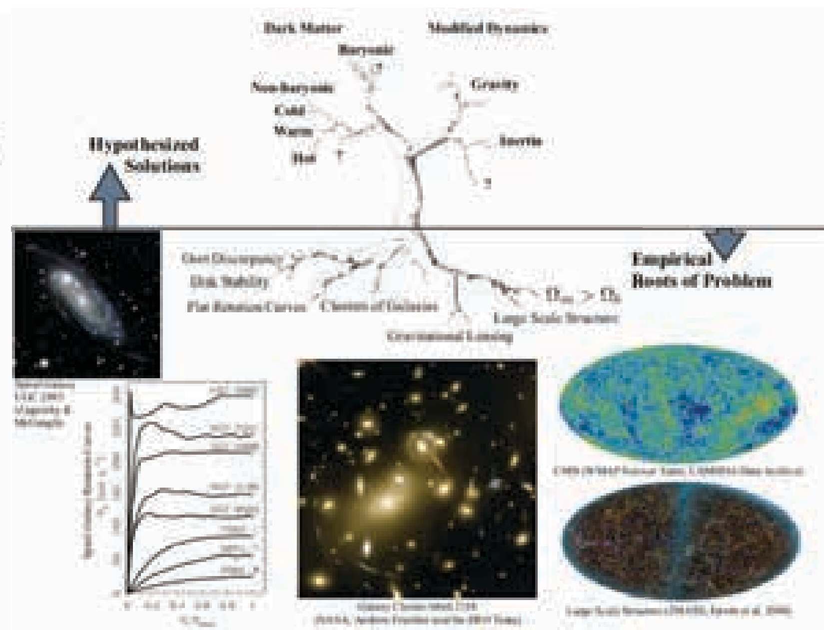
What can drive the late-time cosmic acceleration?

According to modern cosmology, anything can't be explained by the conventional paradigm, it must belong to …

Dark Universe

Modified Gravity beyond Einstein





Chapter 1: Dark energy

- In the sky
- In the mind

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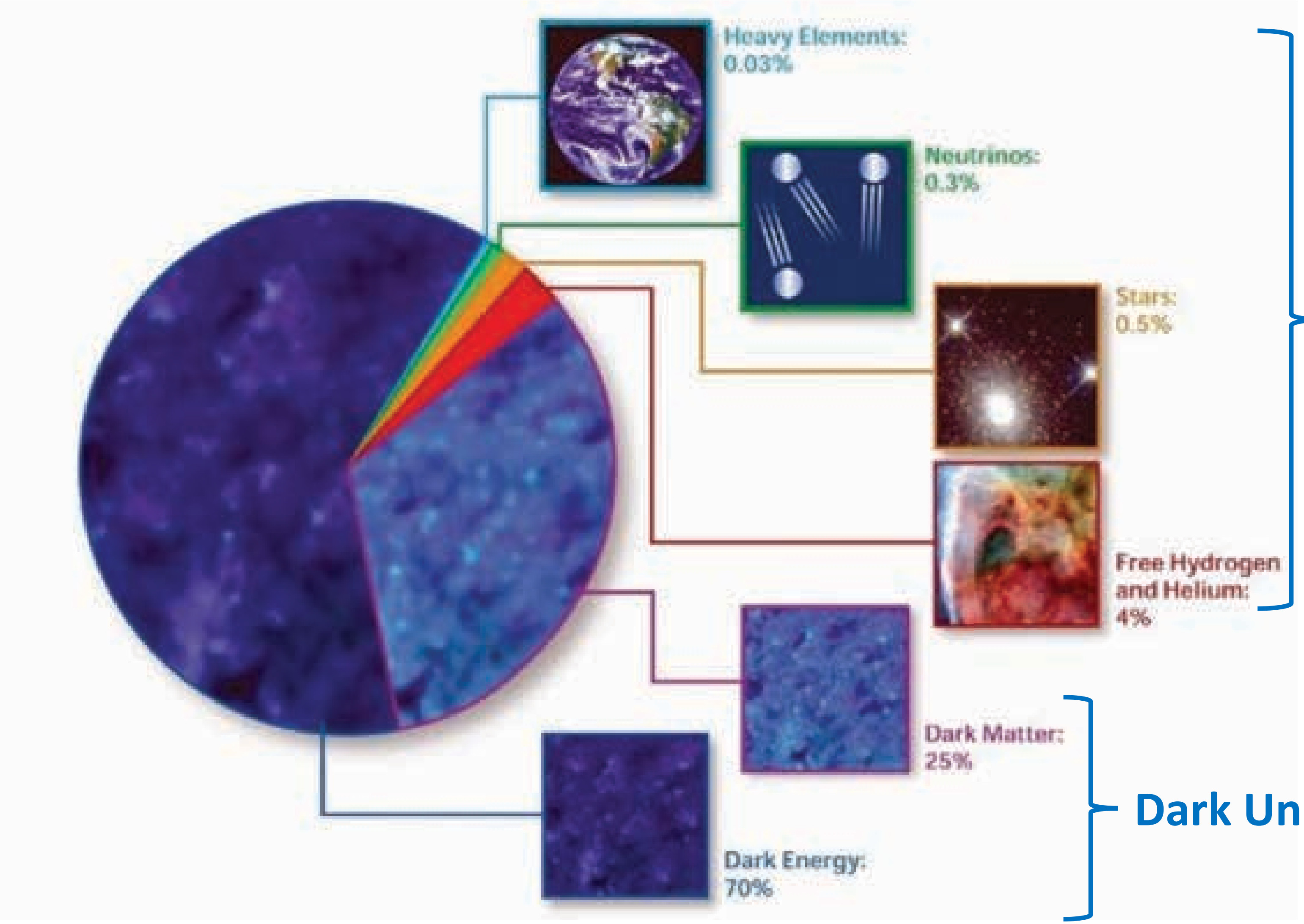
Cosmic Pie



Observable Universe

Dark Universe

Concordance Model

$$\{H_0, \Omega_b, \Omega_c, A_s, n_s, \tau\}$$

Our Universe can be precisely described by the above six cosmological parameters.

H_0: the Hubble expansion rate of the present Universe

Ω_b: the fraction of baryonic matter in the critical density of the present Universe

Ω_c: the fraction of cold dark matter in the critical density of the present Universe

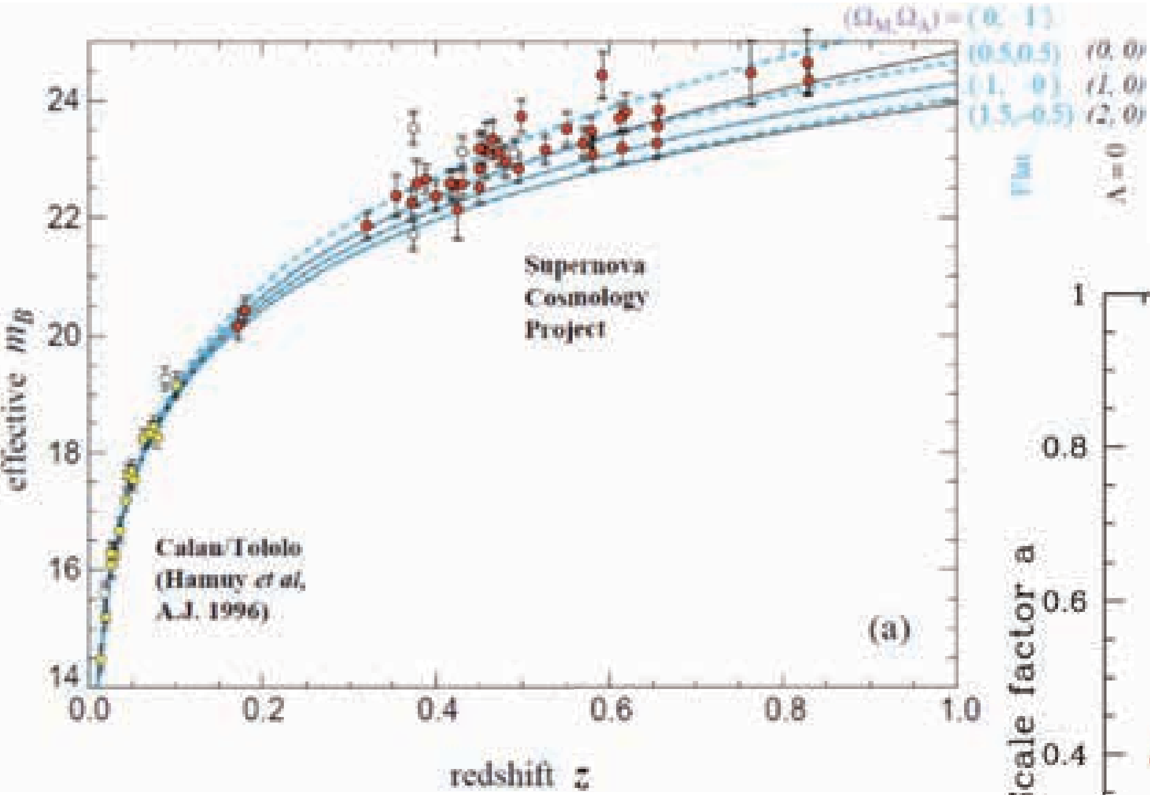
Then, assuming a spatially flat Universe, which btw is consistent with observations

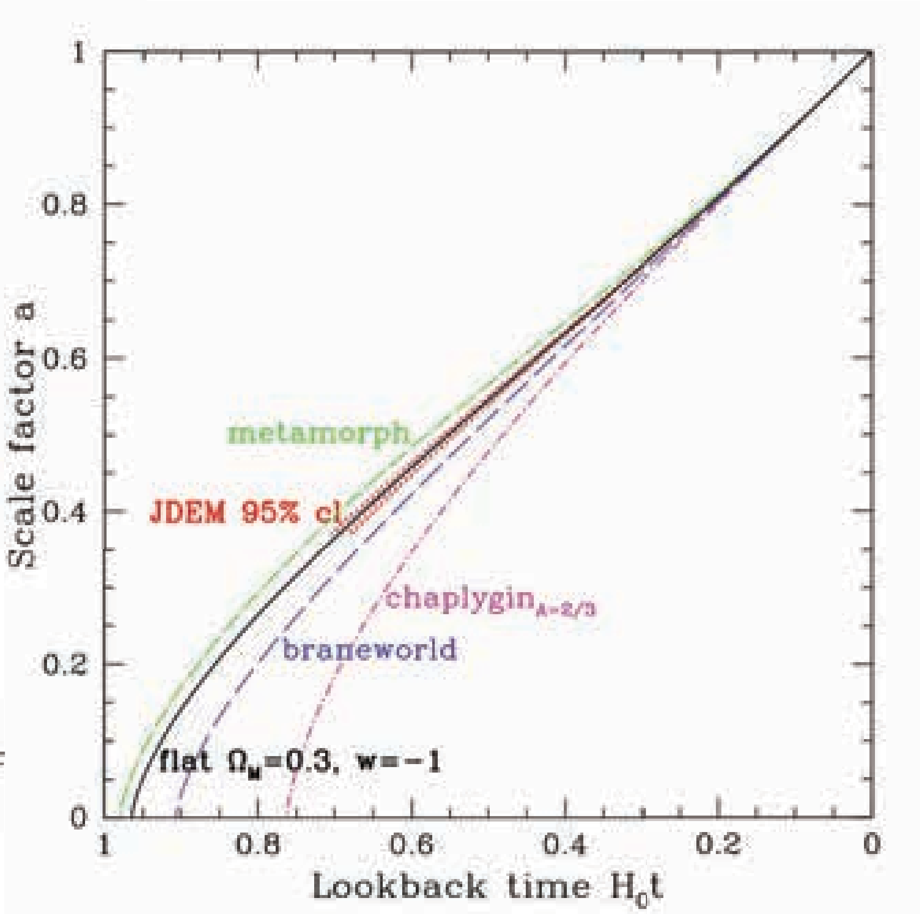
$$\Omega_\Lambda = 1 - \Omega_b - \Omega_c$$

It is the fraction of dark energy in the critical density of the present Universe

- With different parameters, the Universe would have experienced different histories
- The nature of matters is to make the Universe clumping
- Before 1998, we talked about the deceleration parameter q, because we thought the Universe was clumping!

The Great Discovery





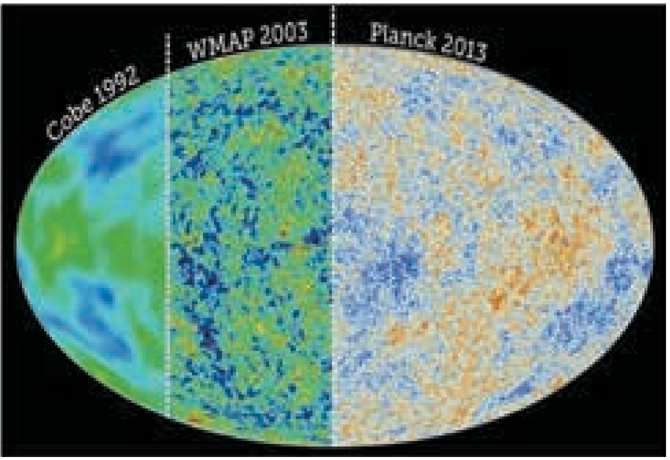
Luminosity distance:

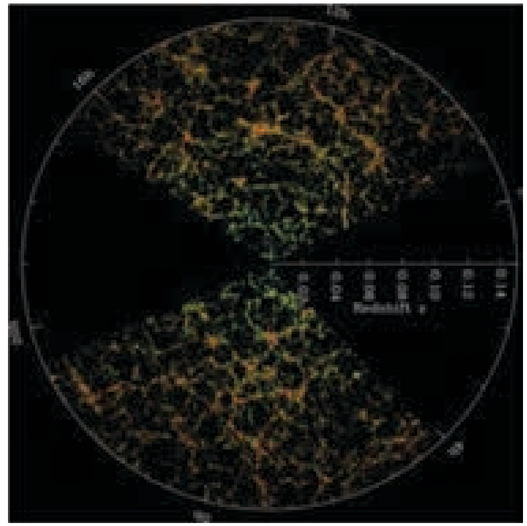
$$d_L(z;H_0,\Omega_M,\Omega_\Lambda)=\frac{1+z}{H_0}\int_0^z\frac{dz'}{\sqrt{\Omega_M(1+z')^3+\Omega_\Lambda}}$$

Observational Windows

We attempt to measure the deceleration parameter q, and it turns out negative!

Our Universe is accelerating → an expectation of dark energy



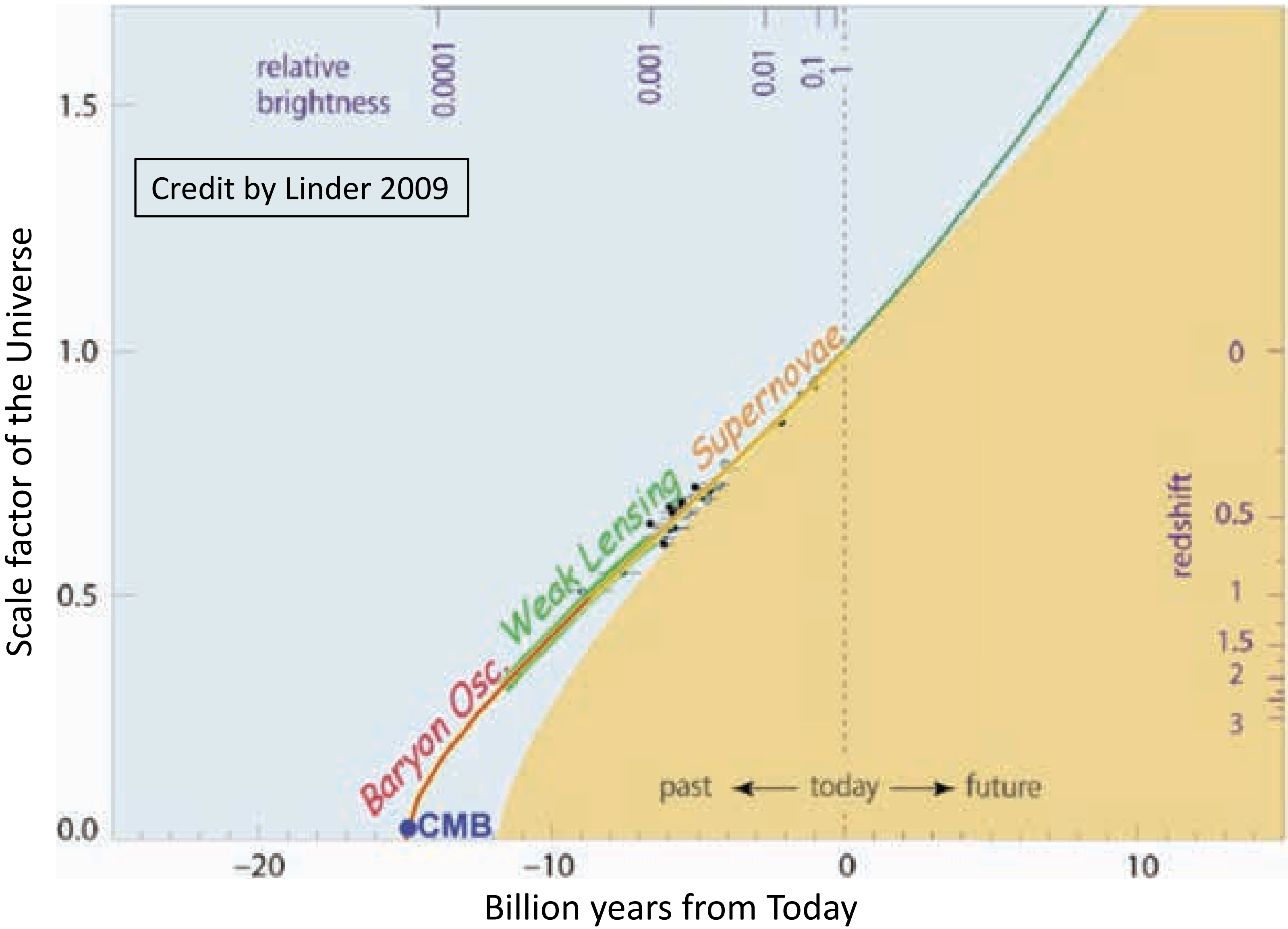


CMB: direct probe of primordial perturbations
Time: 0.003% of the cosmic age

BAO, lensing, matter power spectrum: direct probe of large-scale structure
Time: in between

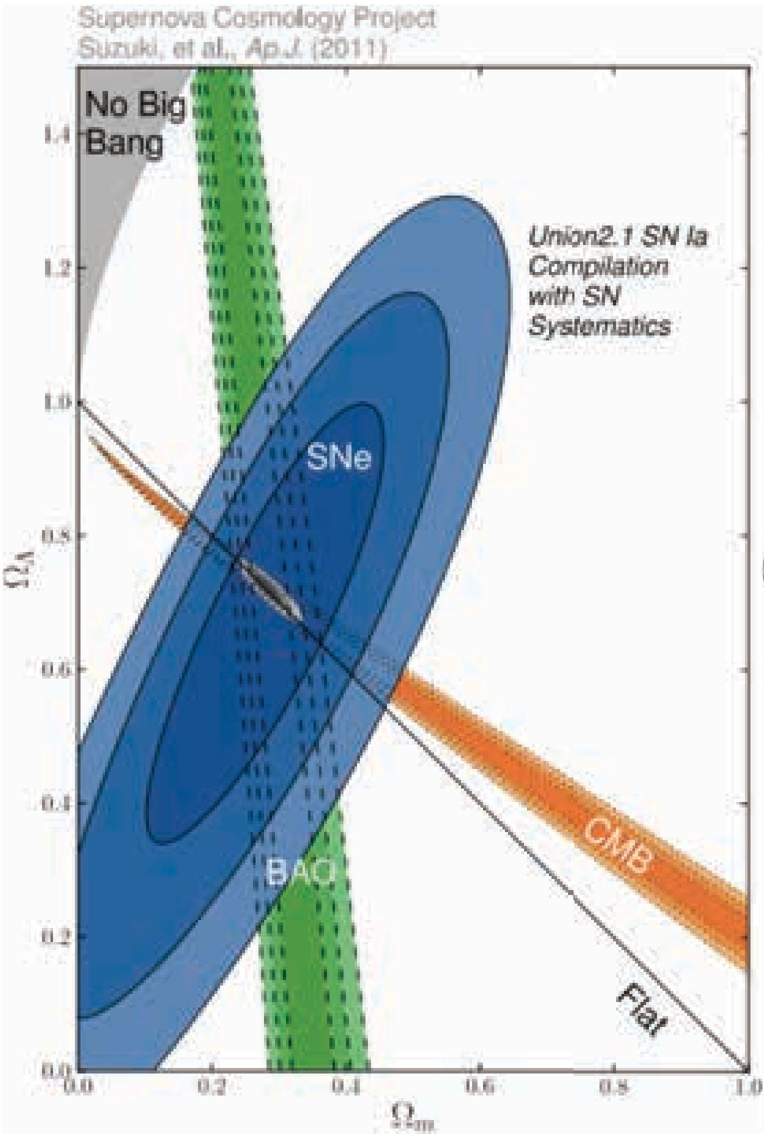
SN: direct probe of cosmic expansion
Time: 30-100% of the cosmic age

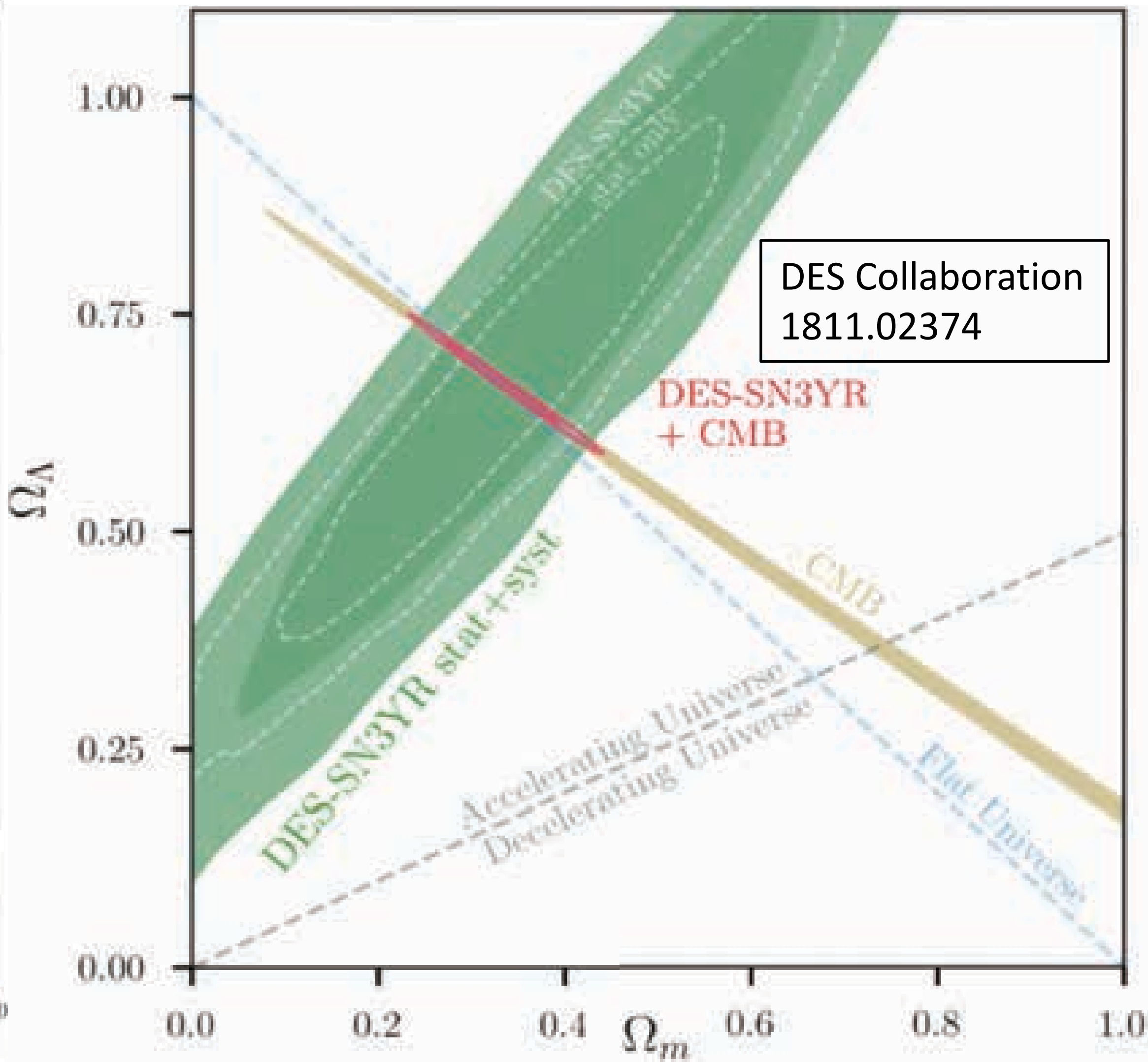
The Expansion History



The Latest Status

$$H_0 = 67.2^{+1.2}_{-1.0}\ \mathrm{km/s/Mpc} \qquad \Omega_\mathrm{m} = 0.331 \pm 0.038$$





DES Collaboration
1811.02374

Chapter 1: Dark energy

- In the sky
- In the mind

Mainly based on *CYF*, Saridakis, Setare, Xia, Phys.Rept. 2010

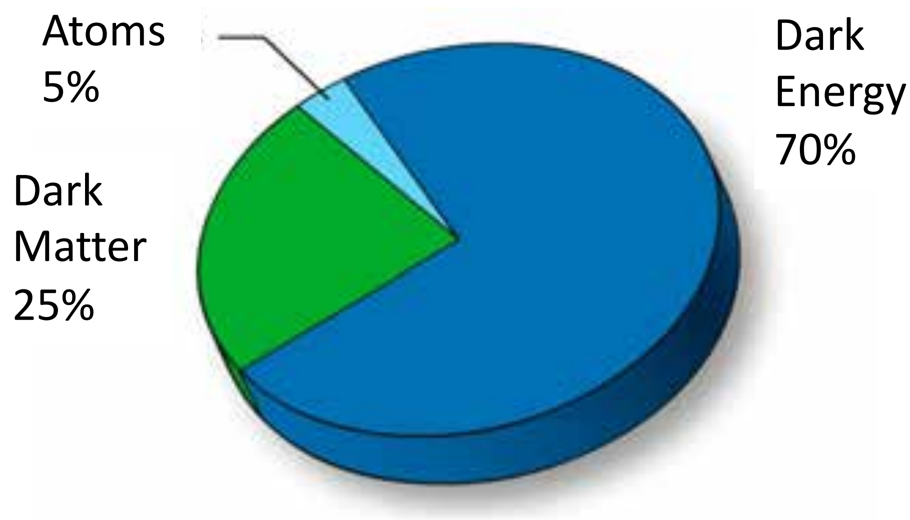
What we know about DE?

Background equation:

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

Acceleration requires: $\ddot{a} > 0$

$$\rho + 3p < 0 \quad w = p/\rho < -1/3$$



Basic features:

- Negative pressure
- Violating strong energy condition
- Almost not clustered at cosmological scales

Theoretical implications:

- Dynamical nature
- Microscopic interpretation
- Possible applications

Cosmological Constant

Originally introduced by Einstein to realize a static universe by "mistake", it has become the simplest candidate of dark energy.

Dynamics: w=-1

Microscopic interpretation: vacuum energy

$$\rho_\Lambda = -p_\Lambda = \frac{\Lambda}{8\pi G} \simeq (2 \times 10^{-3} eV)^4$$

$$\rho_{ob}/\rho_{th} \sim 10^{-120}$$

Weinberg, 1989

- The most severe fine-tuning problem in physics: one needs to cut off vacuum energy by a factor of 1,000,000,000,000, 000,000,000,000, 000,000,000,000, 000,000,000,000, 000,000,000,000, 000,000,000,000, 000,000,000,000, 000,000,000,000, 000,000,000,000, 000,000,000,000.

- Coincidence problem: one cannot explain why such a tiny energy density happens to be comparable with that of matter at today's value, otherwise the universe would look totally different!

Dynamical Fields

Quintessence: Ratra, Peebles, 1988

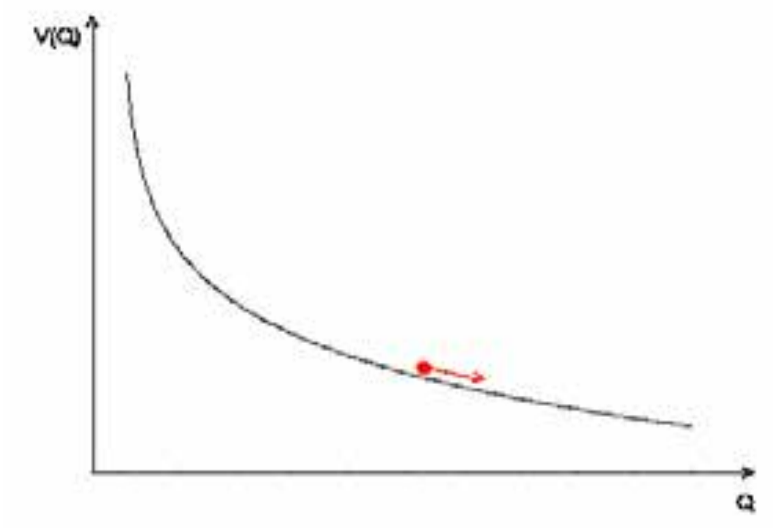
$$\mathcal{L} = \frac{1}{2}\partial_\mu Q \partial^\mu Q - V(Q)$$

$$-1 \leq w_Q \leq 1$$

Phantom: Caldwell, astro-ph/9908168

$$\mathcal{L} = -\frac{1}{2}\partial_\mu P \partial^\mu P - V(P)$$

$$w_P \leq -1$$



Applications:

- For certain potential forms, scalar fields may present tracking behavior to alleviate the coincidence problem
- They may seed cosmological perturbations to affect the large-scale structure of the Universe

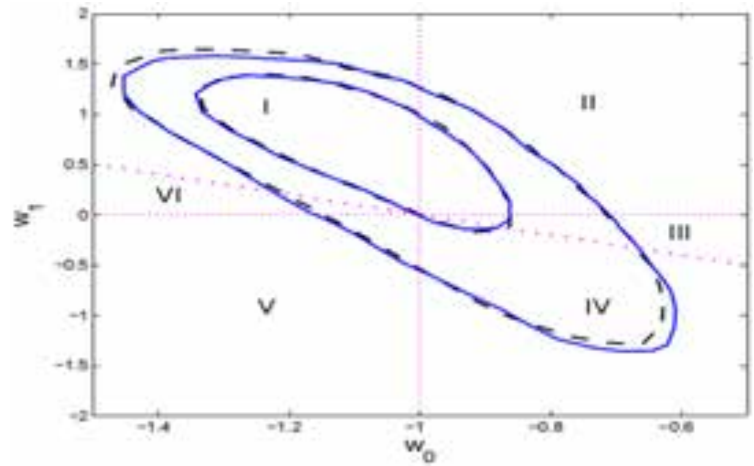
Issues:

- No clues for microscopic origins
- Classical and quantum instabilities

Categories of Dynamics

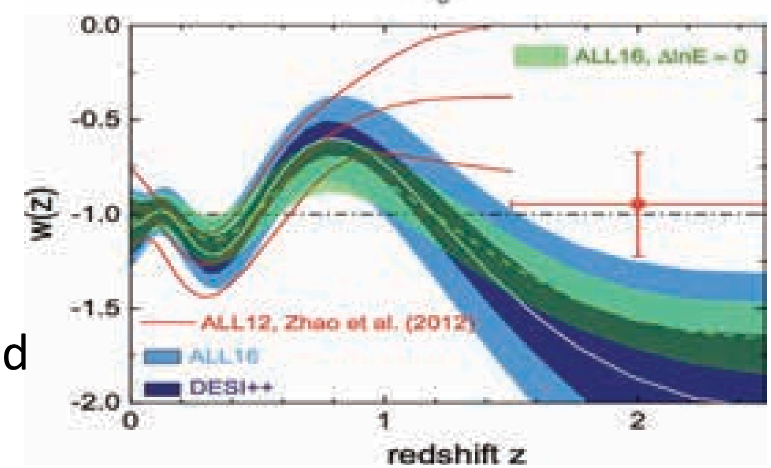
The dynamics of dark energy crucially rely on the equation-of-state parameter, which is defined by the ratio of pressure to energy density

A simple parametrization: $w(a) = w_0 + w_1(1-a)$



Categories:

- Λ: w=-1
- Quintessence: w>-1
- Phantom: w<-1
- K-essence: w>-1 or w<-1
- Quintom: w crosses -1
- Modified gravity: see Chap 2



Status:

- Λ fits well
- Dynamical models are marginally favored

Feng, Wang, Zhang, 2005; Huterer, Cooray, 2005; Xia, et al., 2006; Zhao, et al., 2012, 2017

No-Go Theorem

No-Go theorem:

For theories of dark energy in the 3+1 dimensional FRW universe described by a single perfect fluid or a single scalar field with a generic K-essence Lagrangian, which minimally couples to GR, its EoS parameter cannot cross over the cosmological constant boundary/phantom divide.

CYF, et al., Phys.Rept. 2010
Feng, et al., 2005; Vikman, 2005;
Hu, 2005; Xia, *CYF*, et al., 2008

Key points to the proof:

- For a single perfect fluid, the sound speed square becomes divergent when w=-1 crossing occurs

$$c_s^2 \equiv \frac{\delta p}{\delta \rho} = w - \frac{\dot{w}}{3H(1+w)}$$

- For a single scalar field, there is a general dispersion relation for perturbations, which also becomes divergent when w=-1 crossing occurs

$$\omega^2 = c_s^2 k^2 - \frac{z''}{z} \qquad z \equiv \sqrt{\phi'^2 |\rho_{,X}|}$$

Model Buildings

The Key:

To realize the dynamics of w=-1 crossing over, one ought to break at least one condition presented in the No-Go theorem for dark energy.

Models:

- Gauss-Bonnet Modified gravity – Cai, Zhang, Wang, CTP 2005
- Yang-Mills model – Zhao, Zhang, CQG 2006
- DGP brane-world – Zhang, Zhu, PRD 2007
- Interacting DE – Wang, et al., PLB 2005; RPP 2016
- Effective Lagrangian – *CYF*, et al., PLB 2007; CQG 2008
- Horndeski DE – Matsumoto, PRD 2018
- ……

Applications

Extended perturbation theory:

$$\dot{\delta}_i = -(1+w_i)(\theta_i - 3\dot{\Phi}) - 3\mathcal{H}(1-w_i)\delta_i - 3\mathcal{H}\frac{\dot{w}_i + 3\mathcal{H}(1-w_i^2)}{k^2}\theta_i$$

$$\dot{\theta}_i = 2\mathcal{H}\theta_i + \frac{k^2}{1+w_i}\delta_i + k^2\Psi \,.$$

The parameter space would be enlarged by involving perturbations

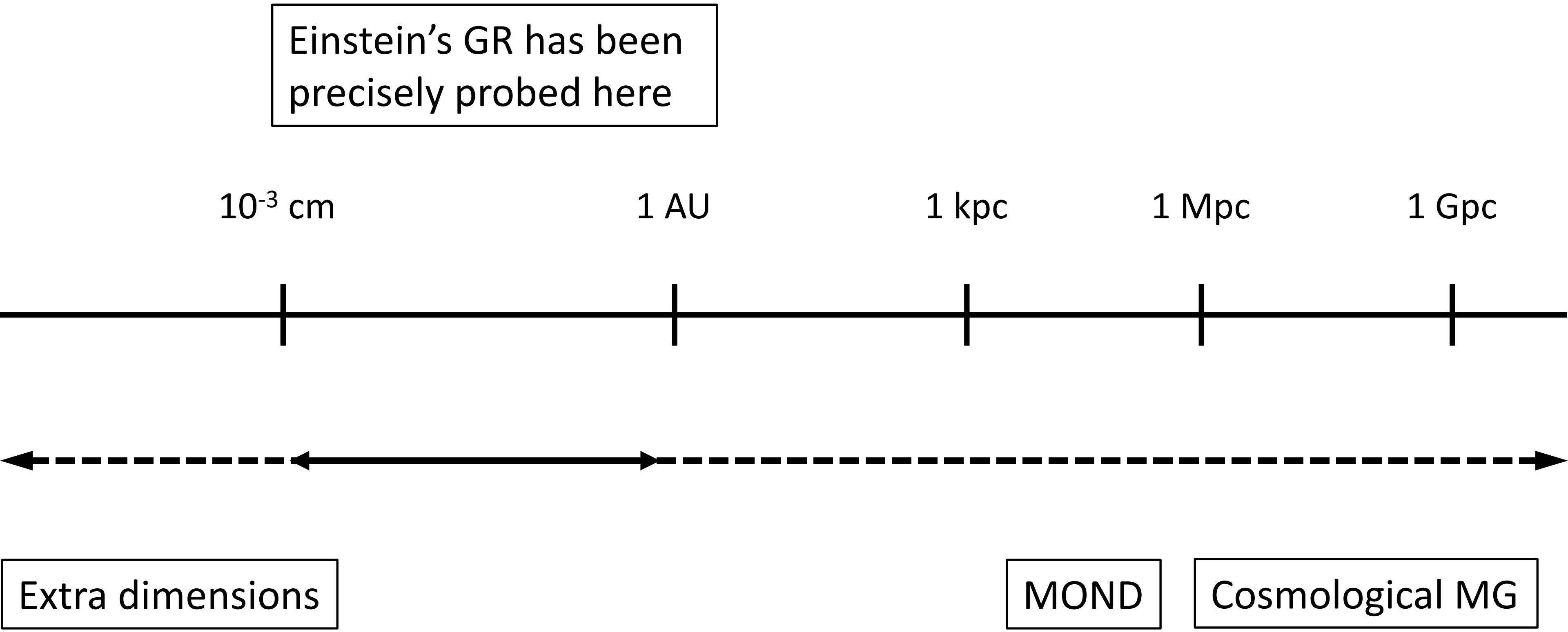
Applications to the primordial Universe:

- Non-singular bouncing cosmologies
  - *CYF*, et al., JHEP 2017; JCAP 2008; SCPMA 2014
- Emergent Universe paradigms
  - *CYF*, et al., PLB 2012; PLB 2014

More applications?

Chapter 2: Modified gravity

What we know about gravity



Why we modify gravity

Theoretical perspective:

Quantum gravity, such as string theory, LQG, SUGRA, generally predicts a modification to GR. Namely, – the scalar-vector-tensor theory

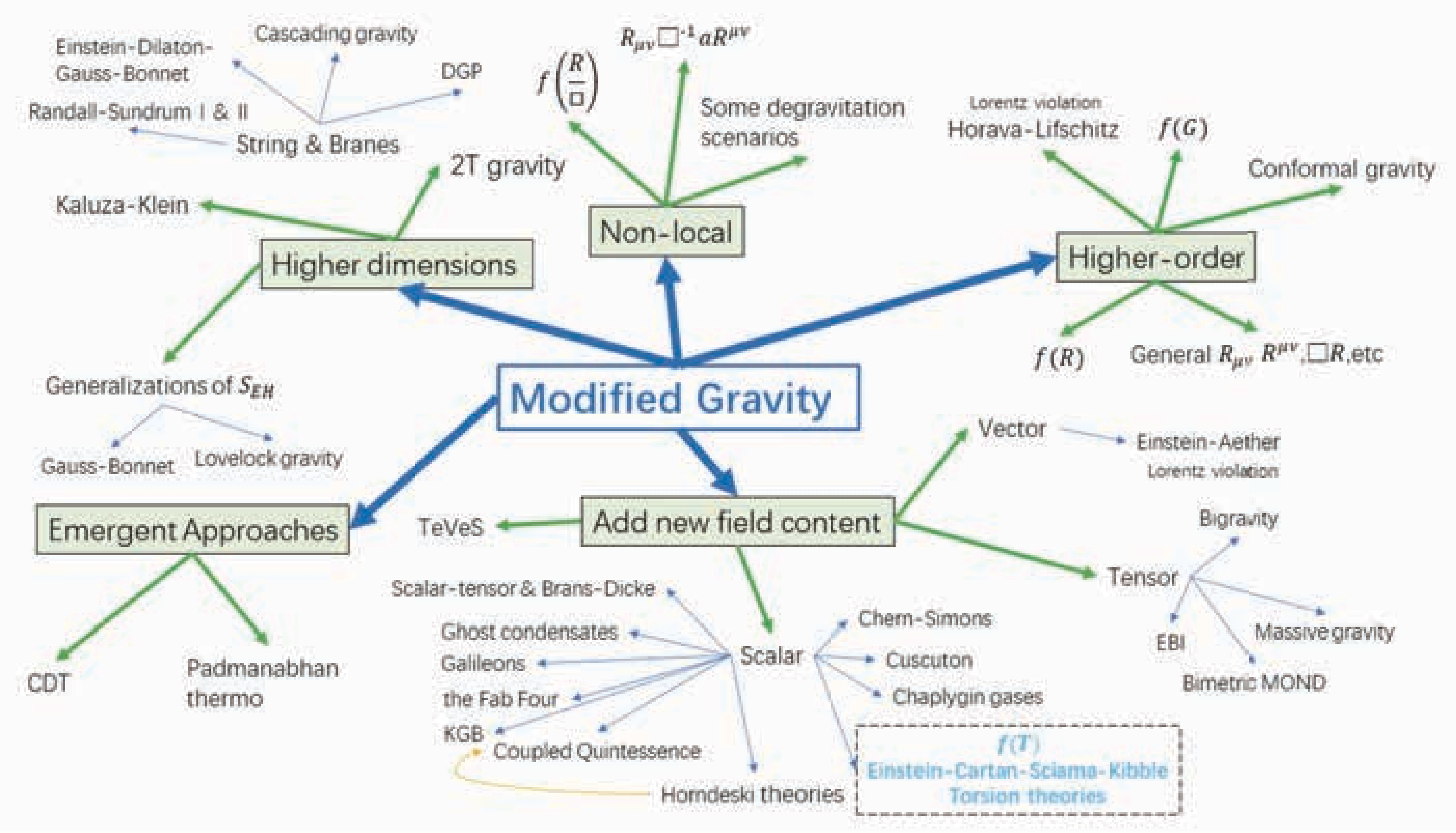
Historical perspective:

- A modification to GR was initiated to explain the anomalous rotation curves of galaxies – MOdified Newtonian Dynamics by Milgrom
- The first and so far most successful inflation model is based on modified gravity – R^2 model by Starobinsky

Phenomenological perspective:

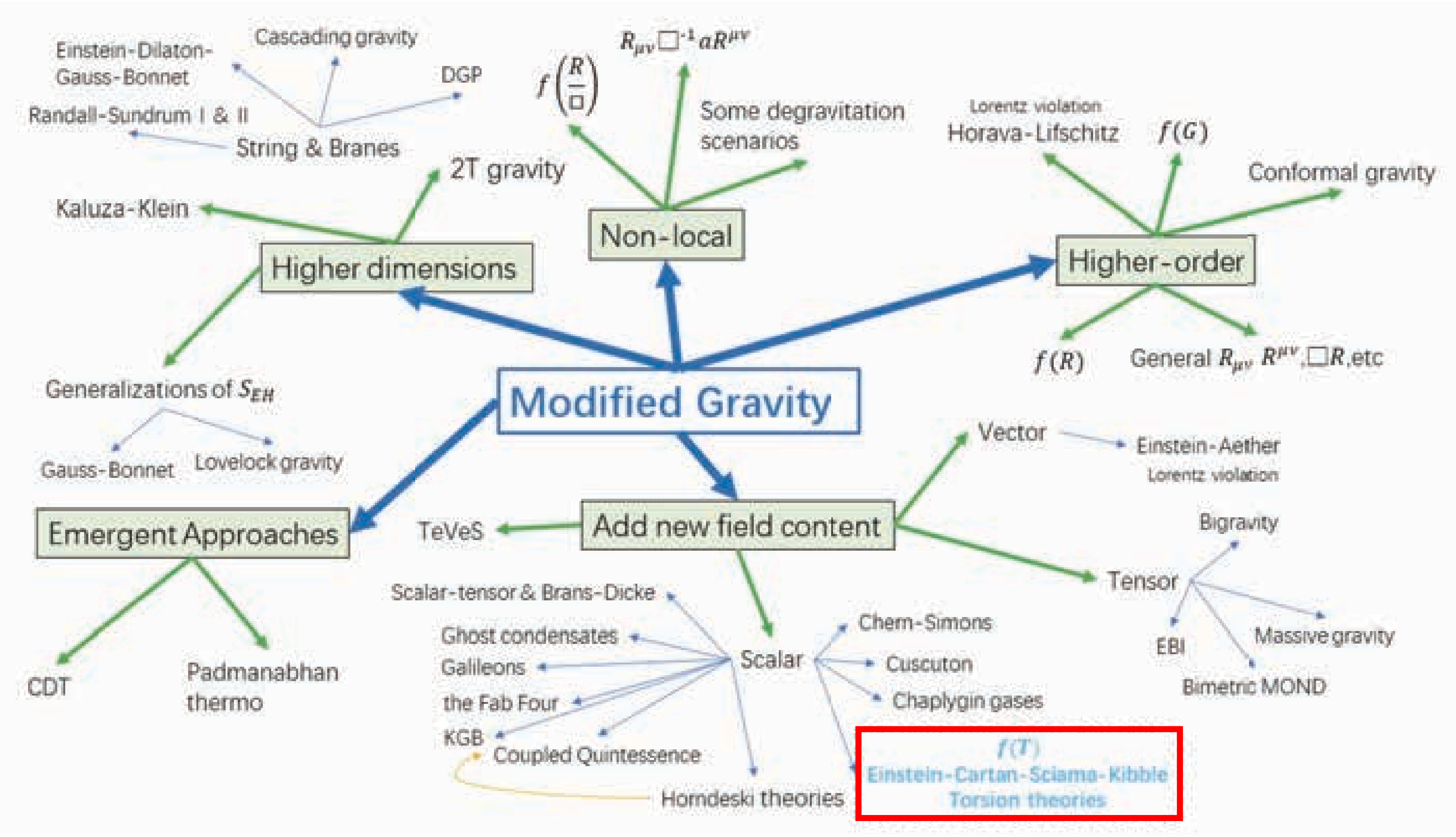
There is no reason that gravity theory can't be altered at cosmological scales so that it can drive cosmic acceleration – F(R) theory

How many MGs



Modified Gravity
Higher dimensions
Non-local
Higher-order
Emergent Approaches
Add new field content
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
DGP
Randall-Sundrum I & II
String & Branes
2T gravity
Kaluza-Klein
$f\left(\frac{R}{\Box}\right)$
$R_{\mu\nu}\Box^{-1}aR^{\mu\nu}$
Some degravitation scenarios
Lorentz violation
Horava-Lifschitz
$f(G)$
Conformal gravity
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$,$\Box R$,etc
Generalizations of S_{EH}
Gauss-Bonnet
Lovelock gravity
Vector
Einstein-Aether
Lorentz violation
Bigravity
TeVeS
Tensor
Scalar-tensor & Brans-Dicke
Chern-Simons
EBI
Massive gravity
Ghost condensates
Scalar
Galileons
Cuscuton
Bimetric MOND
the Fab Four
Chaplygin gases
KGB
Coupled Quintessence
Horndeski theories
CDT
Padmanabhan thermo
$f(T)$
Einstein-Cartan-Sciama-Kibble
Torsion theories

How many MGs



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Torsion theories

Chapter 2: Modified gravity

- Effective field theory of f(T) and beyond

Based on 1801.05827 and 1803.09818, by Li Chunlong, Cai Yong, Xue Lingqin, Emmanuel Saridakis & *CYF*

See also *CYF*, Capozziello, De Laurentis, Saridakis, RPP 2016 for warm-up (121 pages)

Introduction to teleparallel gravity

Metric: $g_{\mu\nu}$ → Tetrad (vierbein): e_{μ}^{A}

Tangent space descriptions:

Associate a tangent space to each spacetime point and work in terms of that tangent space.

The dynamical variable can be regarded as tetrad

$$e_A^{\mu}, \quad \mu, \nu, \rho \ldots = 0,\ 1,\ 2,\ 3, \quad A, B, C = 0,\ 1,\ 2,\ 3.$$

which is an **orthonormal basis** for the tangent space at each point of the manifold.

$$g_{\mu\nu} = \eta_{AB} e_{\mu}^{A} e_{\nu}^{B}$$

$$\eta_{AB} = \eta^{AB} = diag(-1,1,1,1)$$

Introduction to f(T) gravity

Weitzenbock connection: $\hat{\Gamma}^{\lambda}{}_{\mu\nu} \equiv e_A^{\lambda}\partial_\nu e_\mu^A = -\, e_\mu^A \partial_\nu e_A^{\lambda}$

Torsion tensor: $T^{\lambda}{}_{\mu\nu} \equiv \hat{\Gamma}^{\lambda}{}_{\nu\mu} - \hat{\Gamma}^{\lambda}{}_{\mu\nu} = e_A^{\lambda}(\partial_\mu e_\nu^A - \partial_\nu e_\mu^A)$

Torsion scalar: $T = \frac{1}{4} T_{\rho\mu\nu} T^{\rho\mu\nu} + \frac{1}{2} T^{\nu\mu\rho} T_{\rho\mu\nu} - T^{\mu}{}_{\nu\mu} T^{\alpha\nu}{}_{\alpha}$

- Teleparallel Equivalent of General Relativity:

$$S = \frac{M_P^2}{2}\int d^4x \sqrt{-g}(-T) \qquad R = -T - 2\nabla_\mu T^\mu \qquad T^\mu = g^{\mu\nu} T^{\lambda}{}_{\nu\lambda}$$

- The action of f(T) theory: $S = \int d^4x \sqrt{-g} \frac{M_P^2}{2} f(T)$

EFT of teleparallel gravity

The effective field theory (EFT) description of teleparallel gravity:

$$S = \int d^4x\sqrt{-g}\Big[\frac{M_P^2}{2}\Psi(t)R - \Lambda(t) - b(t)g^{00} + \frac{M_P^2}{2}d(t)T^0\Big] + S^{(2)} .$$

$$(T^0 = g^{0\mu}T^{\nu}{}_{\mu\nu})$$

Quadratic action for linear perturbations

For f(T) gravity:

$$\Psi(t) = -f_T(T^{(0)}) ,$$

$$\Lambda(t) = \frac{M_P^2}{2}\left[T^{(0)}f_T(T^{(0)}) - f(T^{(0)})\right] ,$$

$$d(t) = 2\dot{f}_T(T^{(0)}) ,$$

$$b(t) = 0 .$$

f_T is the derivative of f(T) with respect to T

Dark energy in f(T):

$$\rho_{DE}^{\text{eff}} = \frac{M_P^2}{2}\Big[T^{(0)} - f(T^{(0)}) + 2T^{(0)}f_T(T^{(0)})\Big] ,$$

$$p_{DE}^{\text{eff}} = -\frac{M_P^2}{2}\Big[4\dot{H}[1 + f_T(T^{(0)}) + 2T^{(0)}f_{TT}(T^{(0)})] - f(T^{(0)}) + T^{(0)} + 2T^{(0)}f_T(T^{(0)})\Big] .$$

Perturbation theory - scalar

- Scalar perturbations

Newtonian gauge:

$$e^0_\mu = \delta^0_\mu + \delta^0_\mu \phi + a\delta^i_\mu \partial_i \chi ,$$
$$e^a_\mu = a\delta^i_\mu \delta^a_i (1-\psi) + \delta^0_\mu \delta^a_i \partial^i \chi$$

introduced by the violation of the "local Lorentz invariance ".

Poisson equation:

$$k^2\phi = \frac{a^2}{2M_P^2 f_T}\left(1 - \frac{a^2M^2}{M_P^2 f_T H^2 k^2}\right)\delta\rho_m .$$

$$M^2/M_P^2 \sim H^4$$

$$k^2/a^2 \gg H^2$$

$$k^2\phi = \frac{a^2}{2M_P^2 f_T}\delta\rho_m .$$

Effects of the additional scalar χ vanishes.

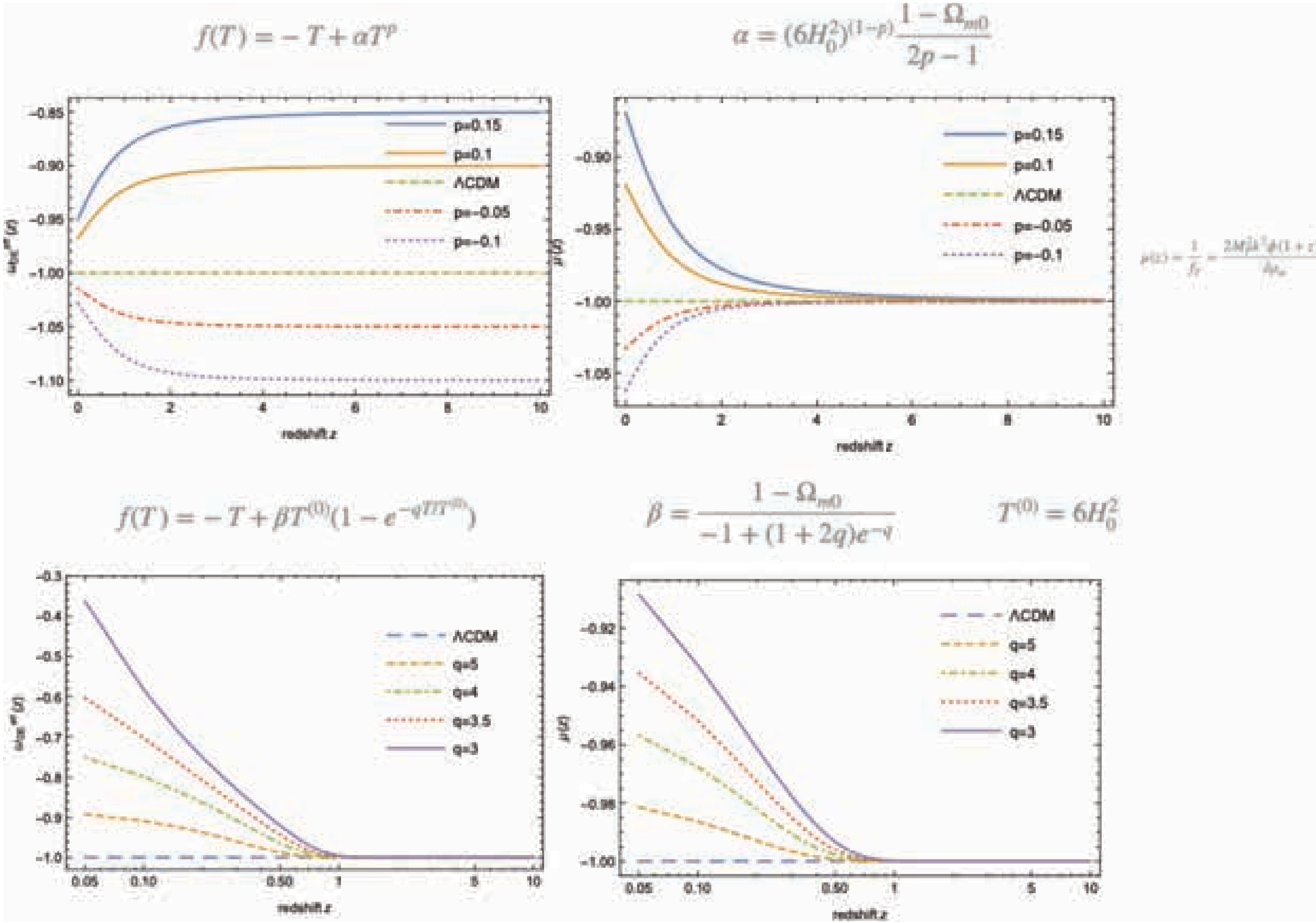
Post-Newtonian parameter:

$$\gamma = \frac{\psi}{\phi} = 1 + \frac{a^2M^2}{f_T H^2 k^2 M_P^2 - a^2M^2} .$$

$$k^2/a^2 \gg H^2$$

$$\longrightarrow \gamma = 1$$

Perturbation theory - scalar



Perturbation theory - tensor

- Tensor perturbations:

$$e^0_\mu = \delta^0_\mu,$$
$$e^a_\mu = a\delta^a_\mu + \frac{a}{2}\delta^i_\mu \delta^{aj} h_{ij},$$

$$S = \frac{M_p^2}{8}\int dt \frac{d^3k}{(2\pi)^3}\, a^3 f_T(\dot{h}^{ij}\dot{h}_{ij} - \frac{k^2}{a^2}h^{ij}h_{ij})$$

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

$$\beta_T = \frac{d\ln f_T}{d\ln T}(1+w_{total})$$

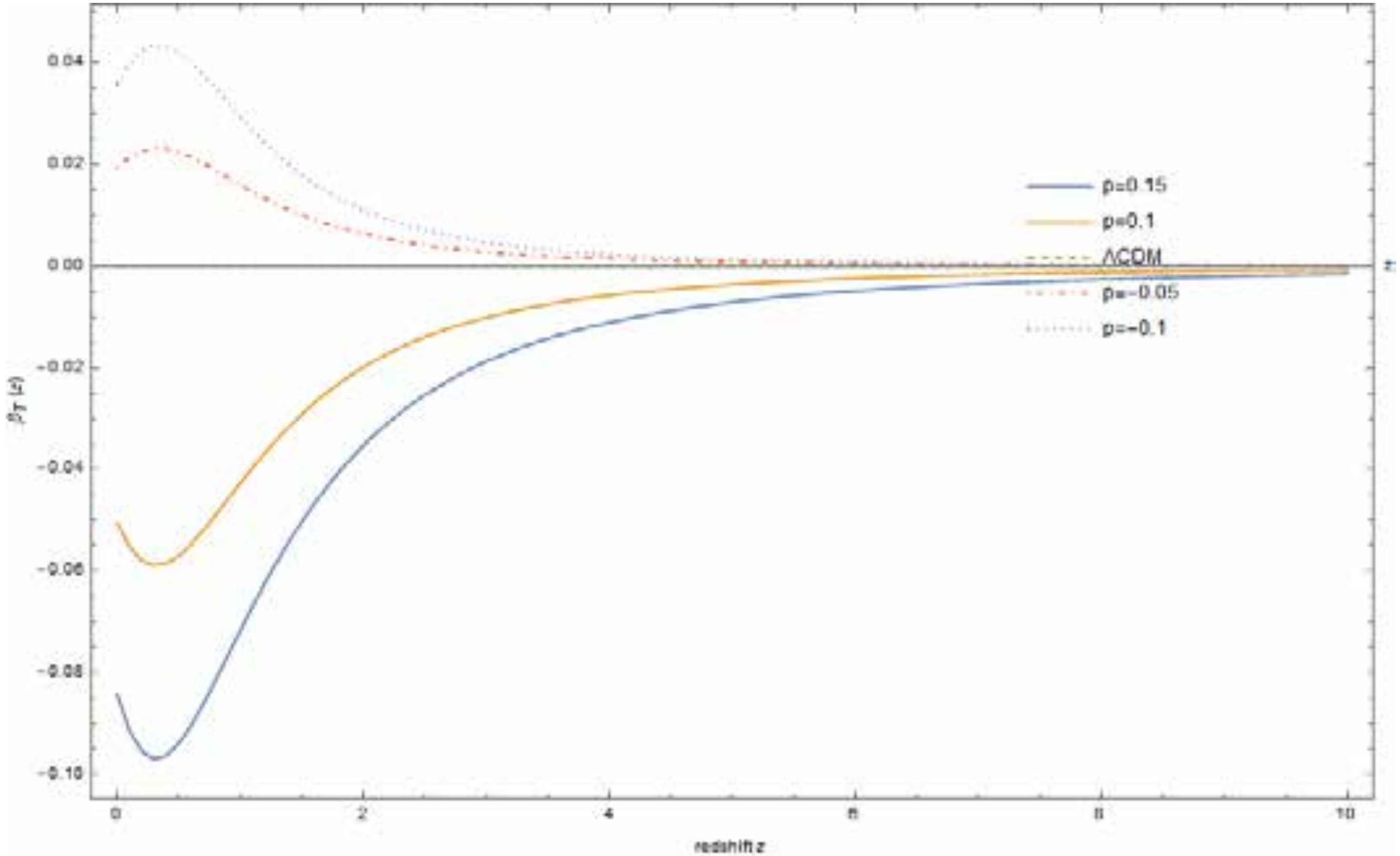
Dispersion relationship:

$$\left|\frac{d\omega}{dk}\right| = \frac{1}{a}\left[1 - \frac{9a^2}{4k^2}H^2(1-\beta_T)^2\right]^{-\frac{1}{2}}$$

Perturbation theory - tensor

$$f(T) = -T + \alpha T^p$$

$$\alpha = (6H_0^2)^{(1-p)} \frac{1-\Omega_{m0}}{2p-1}$$



Summary I

- Our understanding of late-time cosmic acceleration remains far far away from the reality

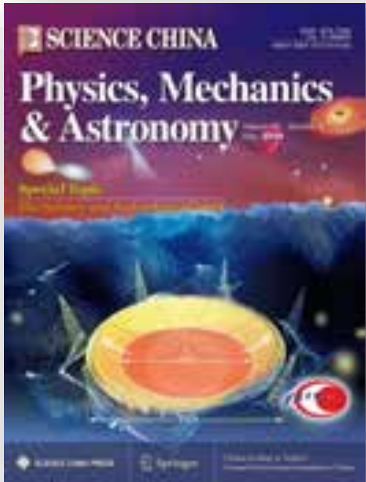
- Dark energy physics:
  - The concordance model of ΛCDM can fit to data well
  - A dynamical model is phenomenologically interesting and marginally indicated by observations
  - The precise measurement of the EoS parameter is crucial in examining the nature of DE
  - A proof of theoretical No-Go makes the DE study become phenomenologically fruitful

Summary II

- Torsional based modified gravity:
  - MG in terms of torsion can be applied to drive cosmic acceleration
  - Teleparallel gravity and extensions can be depicted by EFT dictionary
  - The EFT approach is powerful to help testing this type of MG
  - Different from f(R), there is no propagating dof in pure f(T) gravity
  - The effect of local Lorentz violating scalar dof would be manifest at $k^2/a^2 \sim H^2$
  - Testing f(T) is possible via the measurement of dispersion relations of cosmological GWs in the era of GW astronomy

- Outlook: Accumulated high-precision data from multiple messengers are expected to probe the physics of late-time cosmic acceleration in the future

SCIENCE CHINA-Physics Mechanics & Astronomy



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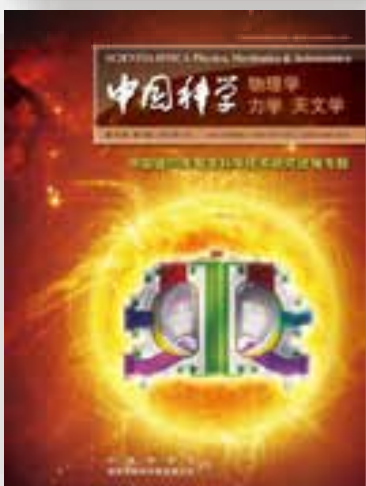

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