Quintom cosmology and modified gravity after DESI 2024

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Quantum Gravity and Cosmology 2024

@ ShanghaiTech University

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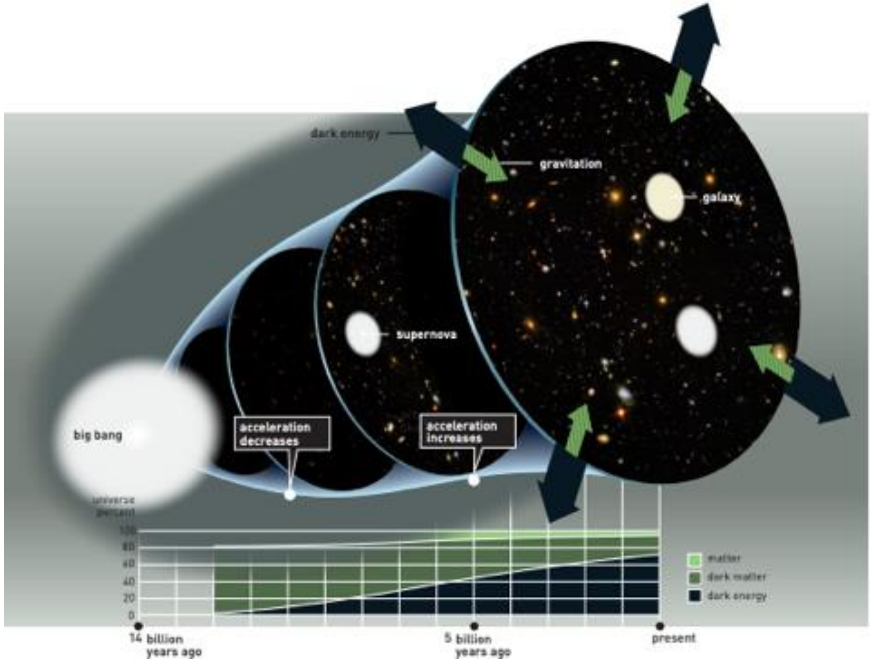
University of Science and Technology of China

Part 1: Introduction of Dark Energy and Modified gravity

Great discovery

A story begins from 1998.

Our Universe is accelerating!



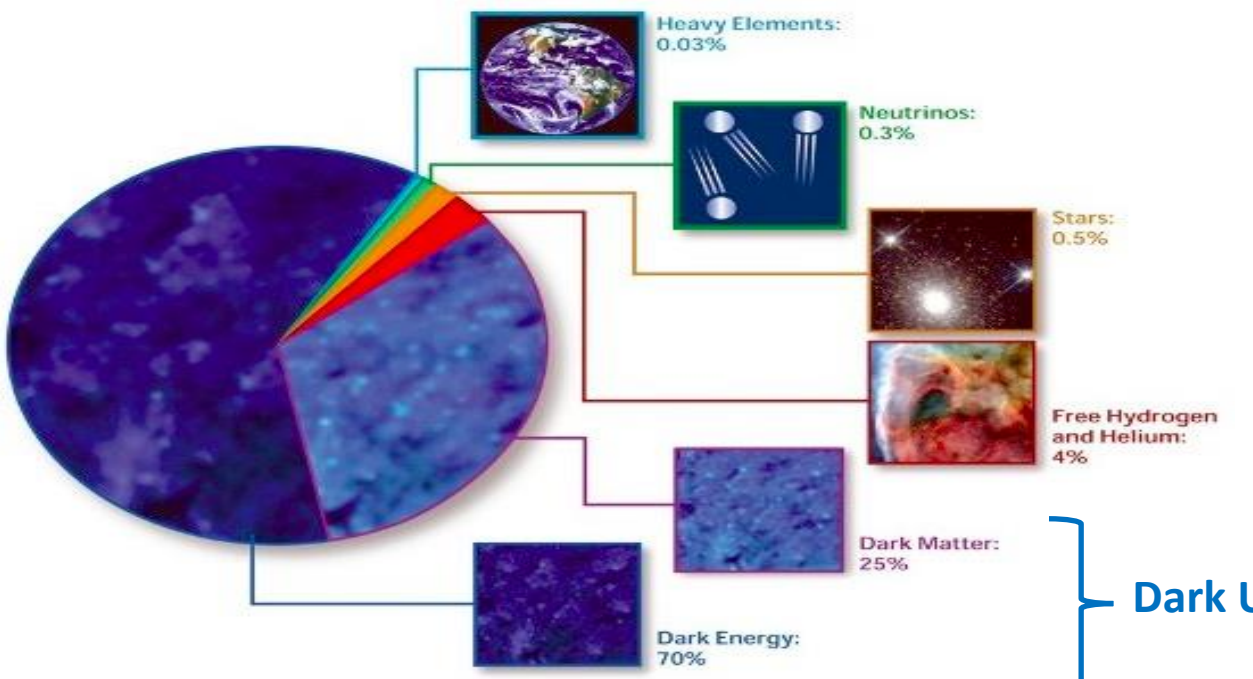
The type-Ia supernovae produces consistent peak luminosity because of the uniform mass of white dwarfs that explode via the accretion mechanism. These explosions can be used as standard candles to measure the distance to their host galaxies since the visual magnitude of the supernovae depends primarily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

Cosmic Pie

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 …

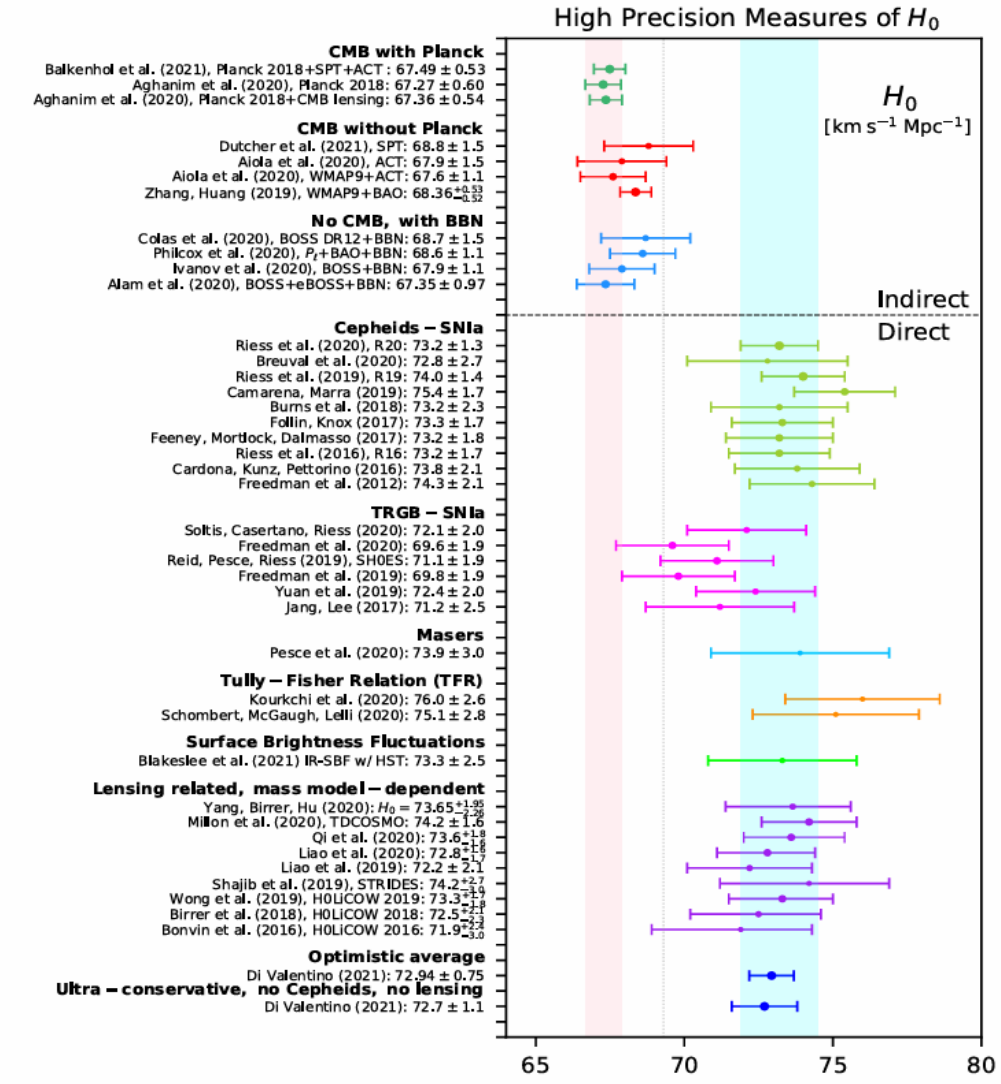
Dark Universe

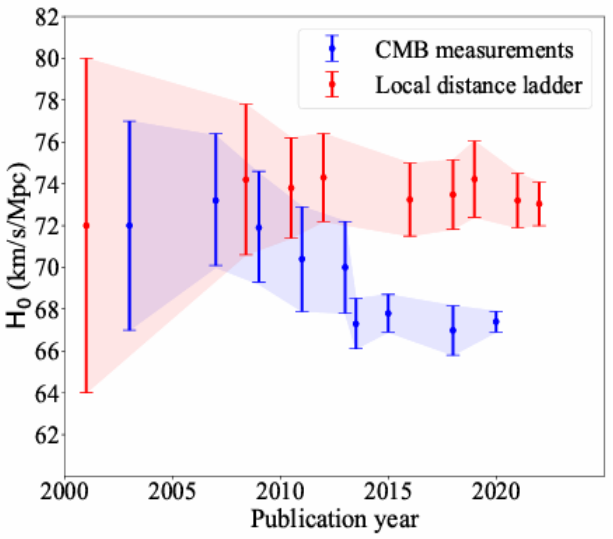


Observable Universe

Dark Universe

Hubble tension





2018: 3.7σ

2019: 4.4σ

Now: 5σ?

Standard ΛCDM model may not be very "standard"!

We may need dynamical dark energy?

Valentino et al, 2103.01183
Hu et al, 2302.05709

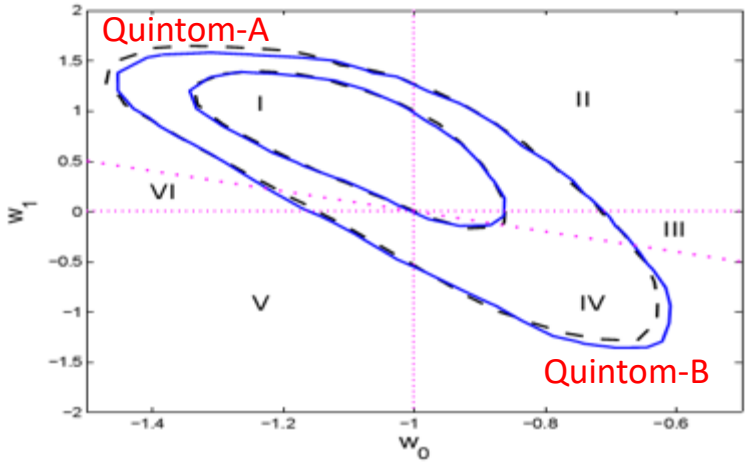
Categories of Dynamics

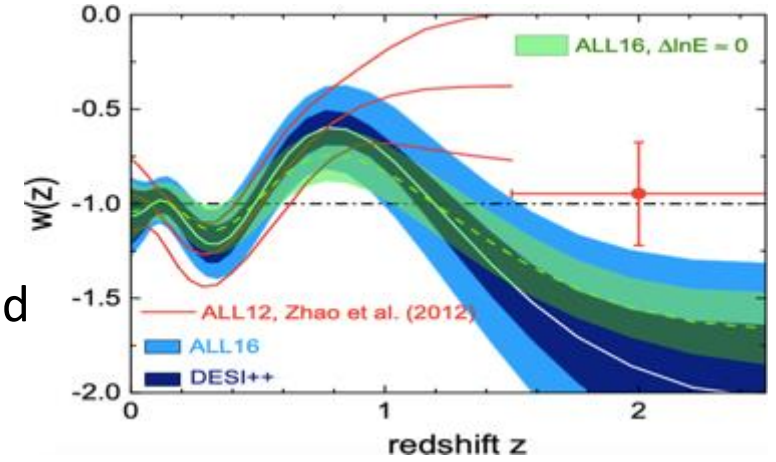
The dynamics of dark energy crucially rely on the equation-of-state parameter, which is defined by the ratio of pressure to energy density

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

Categories:

- Λ: w=-1 ΛCDM
- Quintessence: -1<w<-1/3 II and III
- Phantom: w<-1 V and VI
- K-essence: w>-1 or w<-1
- Quintom: w crosses -1 I and IV





Status:

- Λ is unable to address the dynamics
- Dynamical models are marginally favored

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

Why we modify gravity

Theoretical perspective:

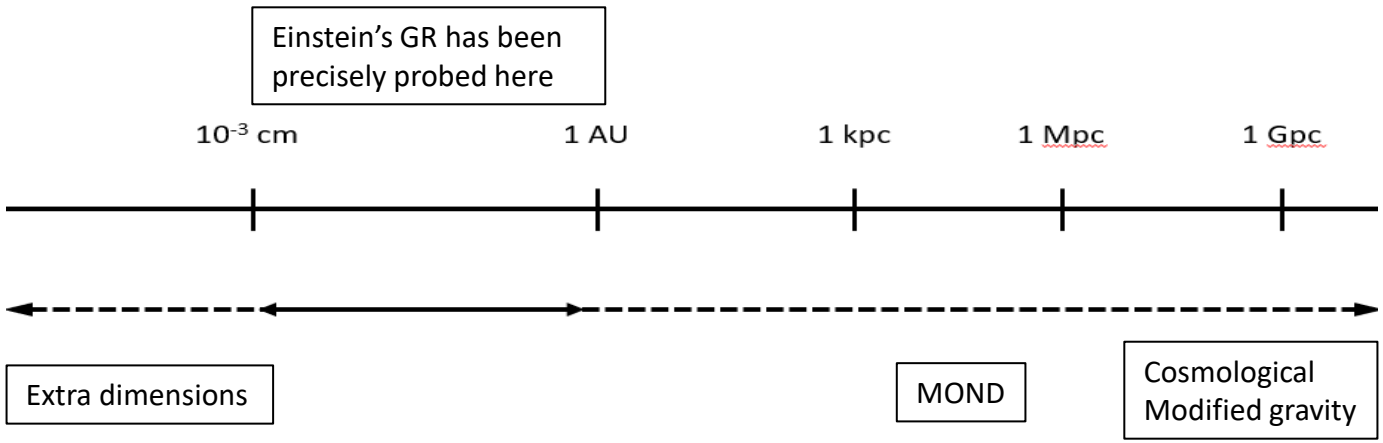
Quantum gravity, such as string theory, LQG, SUGRA, generally predicts a modification to GR.

Historical perspective:

- A modification to GR was initiated to explain the anomalous rotation curves of galaxies – MOdified Newtonian Dynamics by Milgrom (MOND)
- 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



Part 2: DESI 2024 and Cosmological reconstruction

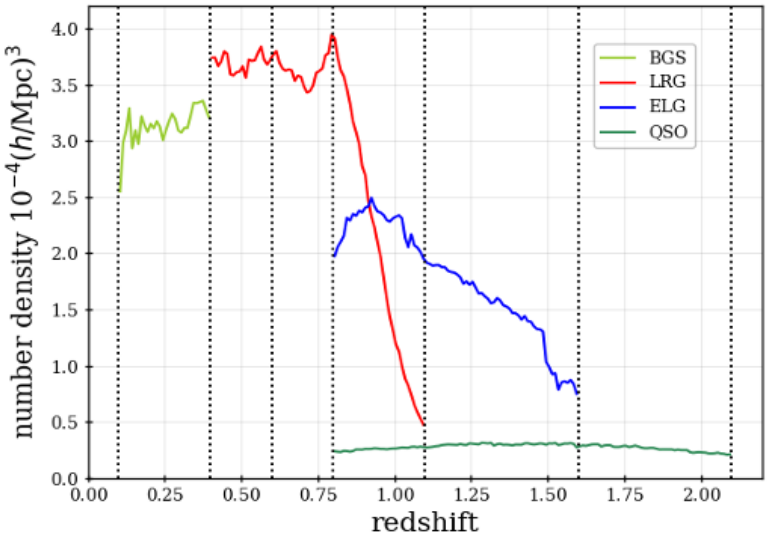
Based on 2404.19437, by ***Yang***, Ren, Wang, Lu, Zhang, Emmanuel Saridakis & Cai

DESI 2024 BAO data

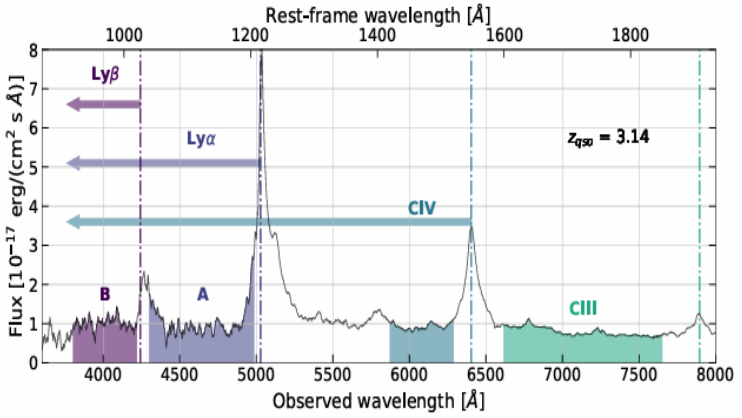
Data combination:

- Bright galaxy sample (0.1-0.4)
- Luminous red galaxy sample (0.4-1.1)
- Emission line galaxy sample (0.8-1.6)
- Combined LRG and ELG (0.8-1.1)
- Quasar sample (0.8-2.1)
- Lyman-alpha forest sample (1.77-4.16)

DESI Collaboration: A.G. Adame et al., 2024
2404.03000, 2404.03001, 2404.03002



From galaxies and quasars at z<2.1 (DESI 2024 III)



From the Lyman-alpha forest at z>2.1 (DESI 2024 IV)

Gaussian Process

Method: **Gaussian Process**, a stochastic procedure to acquire a Gaussian distribution over functions from observational data.

Marina Seikel, et al, JCAP06, 036 2012
Arman Shafieloo, et al, PRD.85.123530

Key points:

- The observation data we get are some data points with error bar at different redshifts independently.

$$y = \{y(x) : x \in \mathcal{X}\}$$

- To understand the law of the function we will reconstruct, we only need consider the finite dimensional distributions (FDDs) for all n∈N.

$$\mathbb{P}(y(x_1) \leq c_1, \ldots, y(x_n) \leq c_n)$$

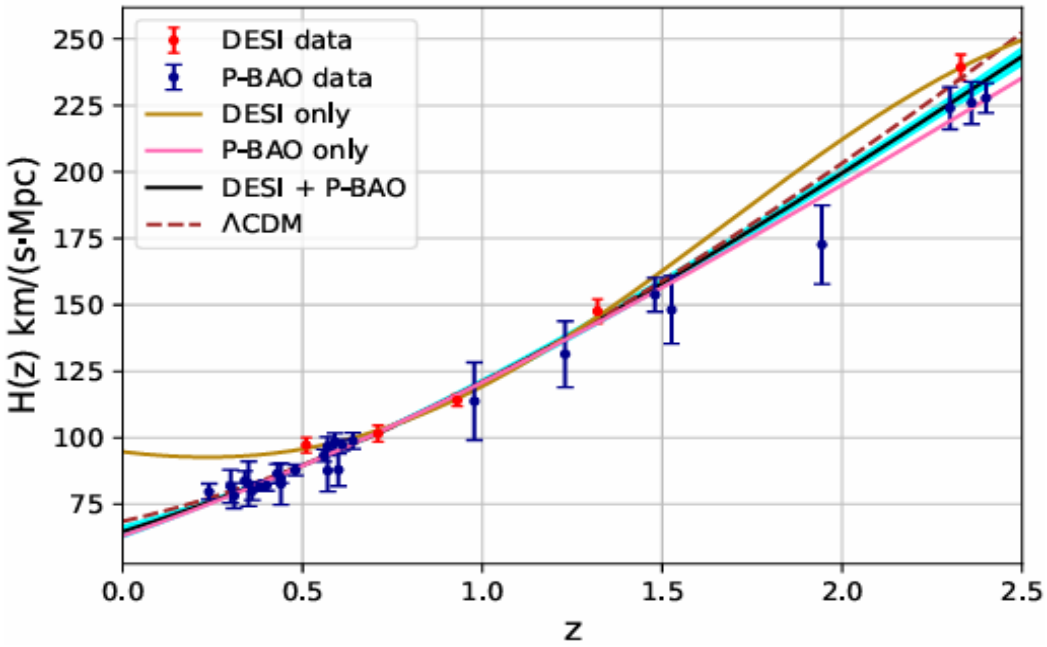
- Gaussian process is a stochastic process with Gaussian FDDs.

$$(y(x_1), \ldots, y(x_n)) \sim N_n(\mu, \Sigma)$$

- We apply GAPP (Gaussian Processes in Python) to reconstruct H(z) and its derivatives through observational data points.

Reconstruction of H(z)

- DESI only is not enough to be well reconstructed, one needs to add more BAO data from SDSS and Wigglez.
- The difference between ΛCDM can be well distinguished at high redshift.
- DESI data at z=0.51 is larger than other observations around the same redshift: **2.44σ** away from the P-BAO only; **2.42σ** away from DESI + P-BAO.



Yang, et al., 2404.19437;
DESI Collaboration 2405.04216, 2405.13588

Quintom-B dark energy

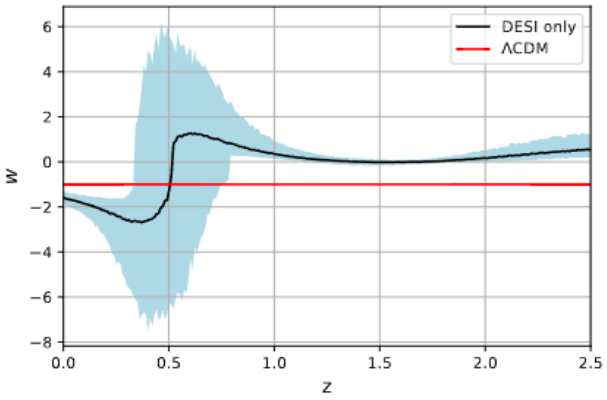
- The equation-of-state of dark energy can be determined by the Hubble parameters and its derivatives model-independently.

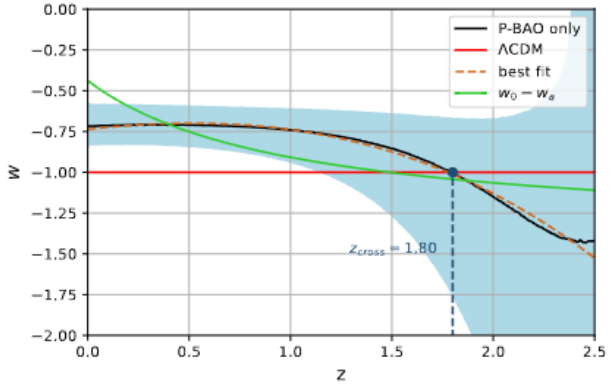
$$w = \frac{-2\dot{H} - 3H^2 - \rho_m}{3H^2 - \rho_m}$$

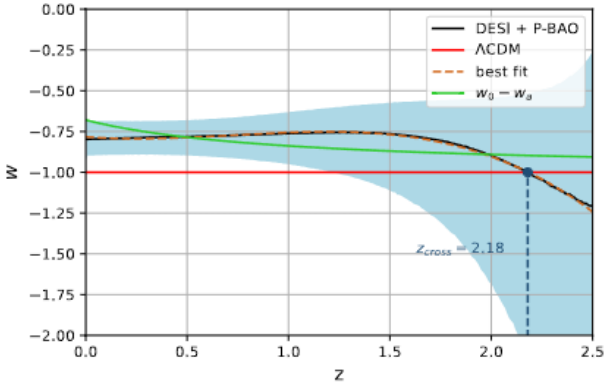
Yang, et al., 2404.19437

- w(z) exhibits a quintom-B behavior, which implies that w can cross −1 from the phantom phase to quintessence phase for P-BAO only and combination.

- The confidence of the quintom-B dynamics using the Monte Carlo simulation and obtain results of 0.93σ and 0.78σ for P-BAO only and DESI + P-BAO.





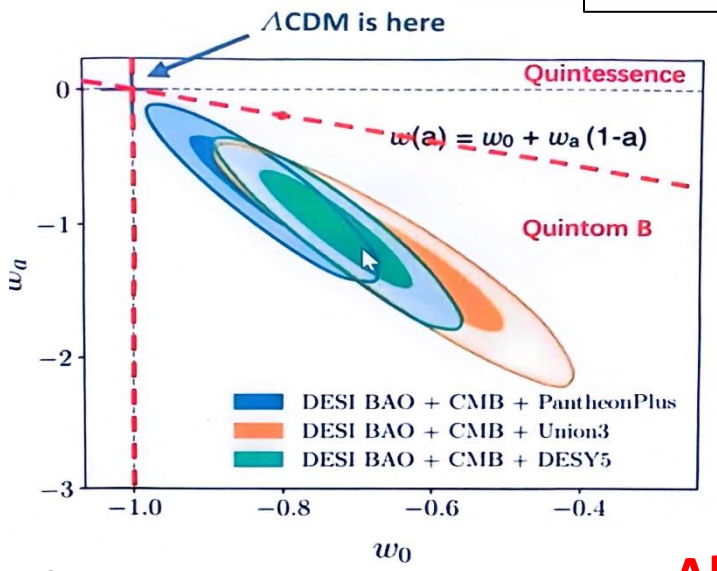


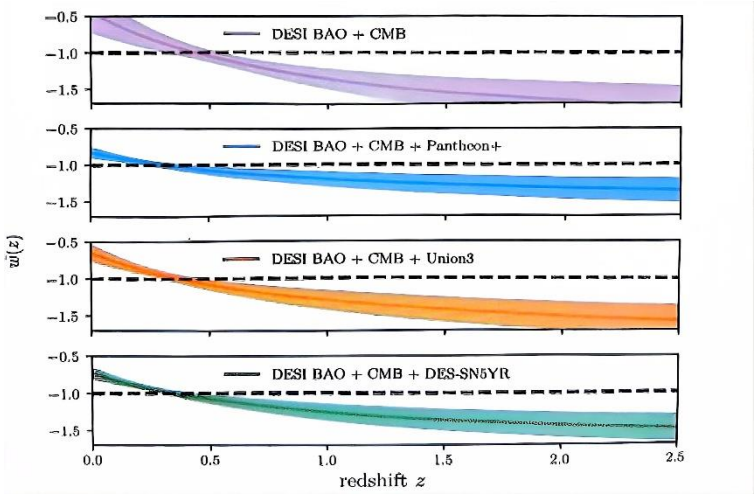
- Traditional w0-wa parametrization of dark energy may not be very sufficient. The mean value curve can be parametrized as $w(z) = a + bz + cz^2 + dz^3,$

How is our analysis different?

w0-wa parametrization:

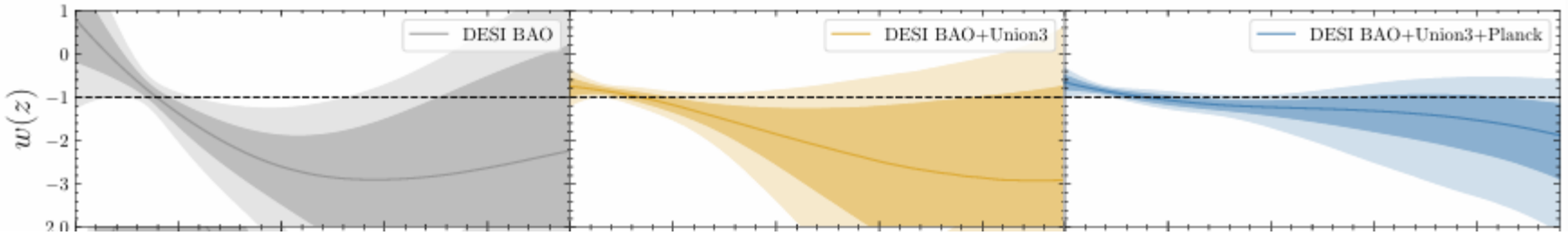
Marina et.al. 2404.08056, DESI Collaboration, Calderon et.al. 2405.04216





Chebyshev expansion:

All quintom-B!



We use a model-independent way to capture the dynamical characteristic of dark energy — — quintom-B!

How to realize such a quintom-B behavior of dark energy from theory?

Part 3: Theoretical implications

Based on 2404.19437, by ***Yang***, Ren, Wang, Lu, Zhang, Emmanuel Saridakis & Cai

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 equation-of-state 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

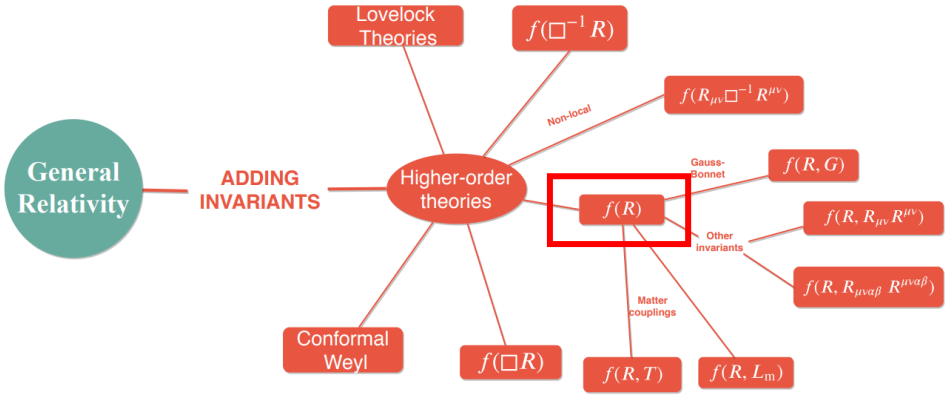
The Key: To realize the dynamics of w=-1 crossing over, one ought to break at least one condition presented in the No-Go theorem for dark energy.

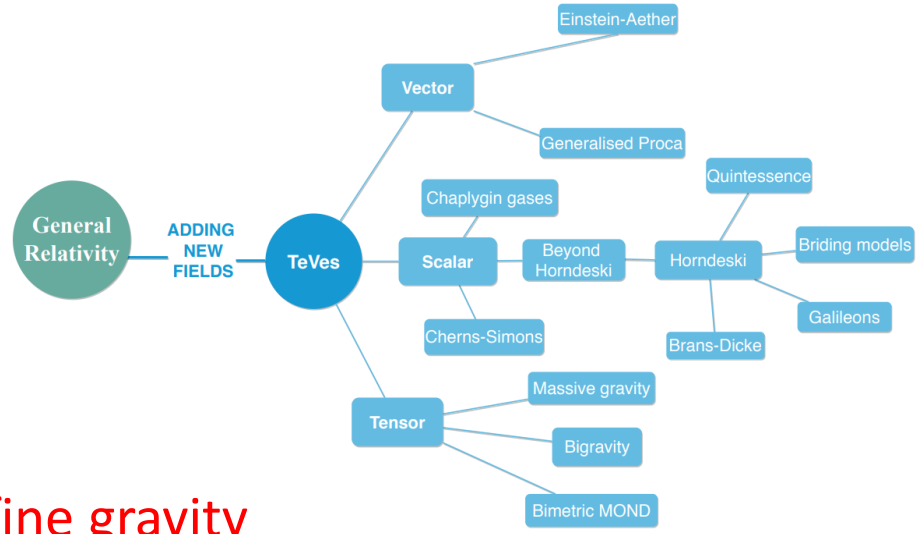
Models:

- 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
- Modified gravity theory
- ……

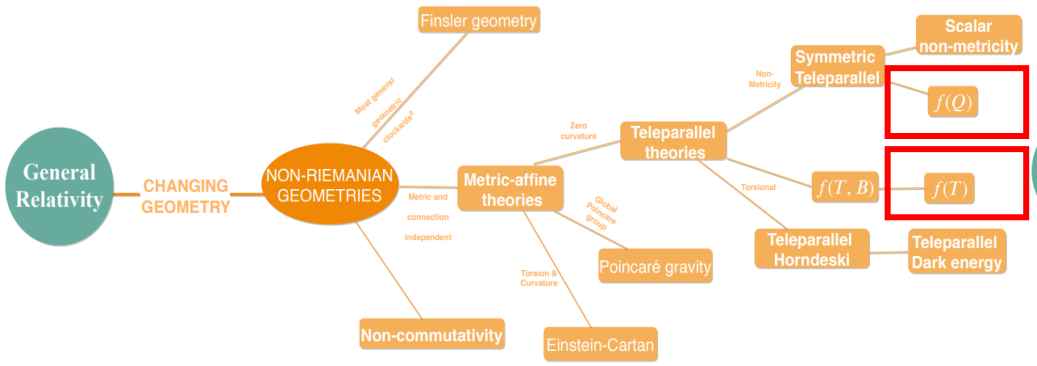
How many MGs

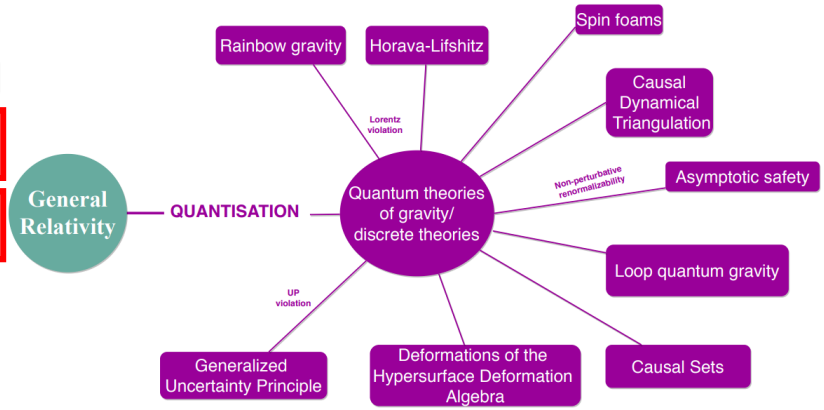
Emmanuel N. Saridakis et al., 2023





Metric-Affine gravity





Metric-Affine gravity

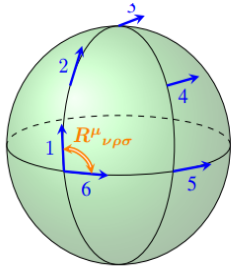
- **Metric-Affine gravity**
  - **f(R)** gravity —— curvature
  - **f(T)** gravity —— torsion
  - **f(Q)** gravity —— non-metricity

(All affine connections are zero!)

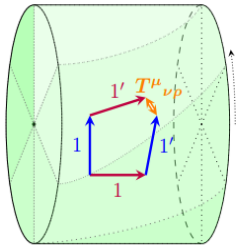
- For f(Q) gravity with **coincident gauge**, it consists with f(T) gravity.

General action, where X represents R, T or Q

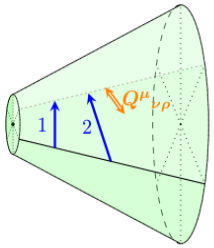
$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}f(X) + \mathcal{L}_m\right] ,$$



curvature



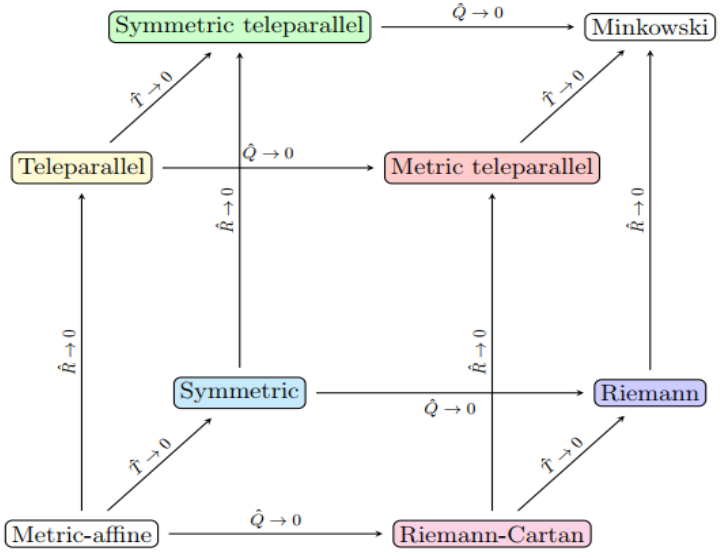
torsion



non-metricity

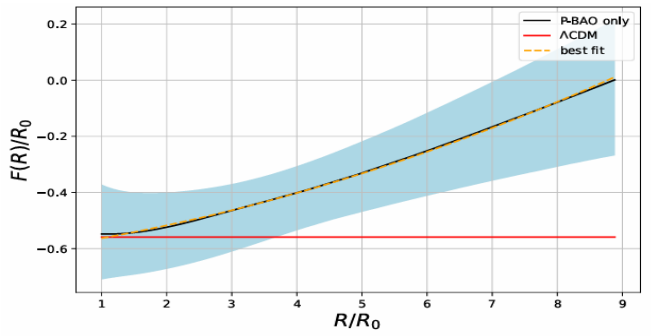
Spacetime geometries

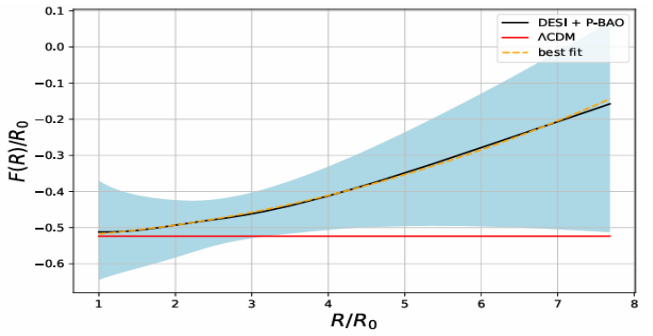
Sebastian Bahamonde et al., 2023

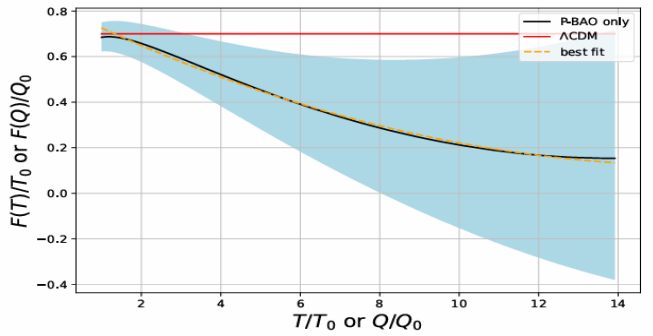


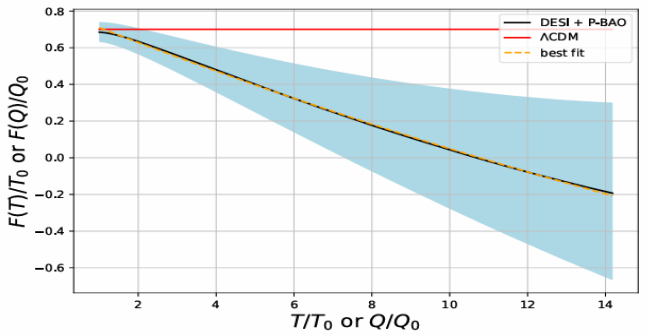
Metric-Affine spacetime

Gravitational interpretations









The reconstructed f(X) can be effectively parametrized as

$$F(X)/X_0 = A + BX/X_0 + CX^2/X_0^2 \ ,$$

Yang, et al., 2404.19437

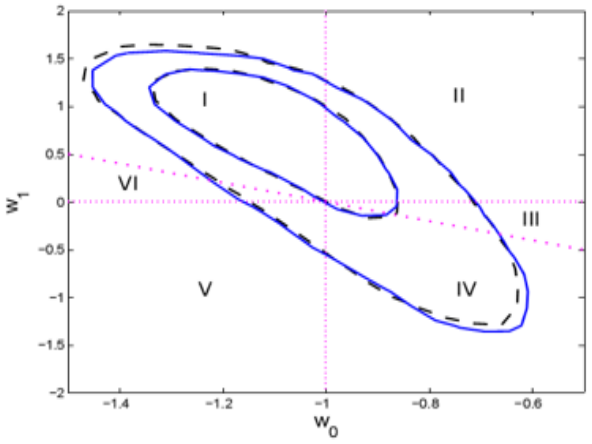
- The reconstruction results indicate f(X) beyond the standard ΛCDM.
- For all cases, the quadratic deviation from ΛCDM is mildly favored.

We just show a simple example to explain this quintom behavior, we hope our work can foster a bridge for future precise cosmological observations and theoretical mechanisms.

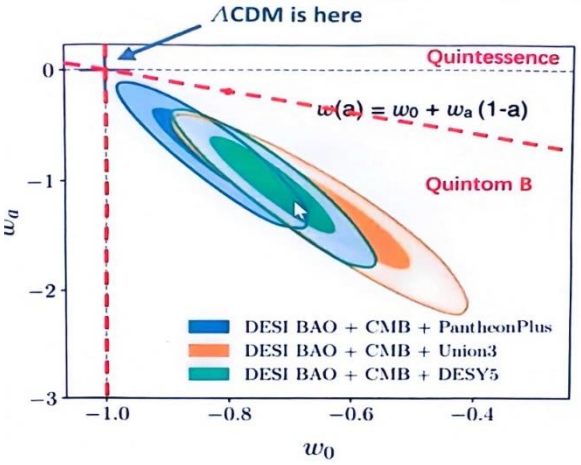
To B or not to B ?

w0-wa parametrization:

Past



Now



Future

Will the confidence of the quintom-B behavior become larger and larger in the future? Or it is wrong?

Dark Energy (Quintom-B) tension?

Part 4: Summary and Outlook

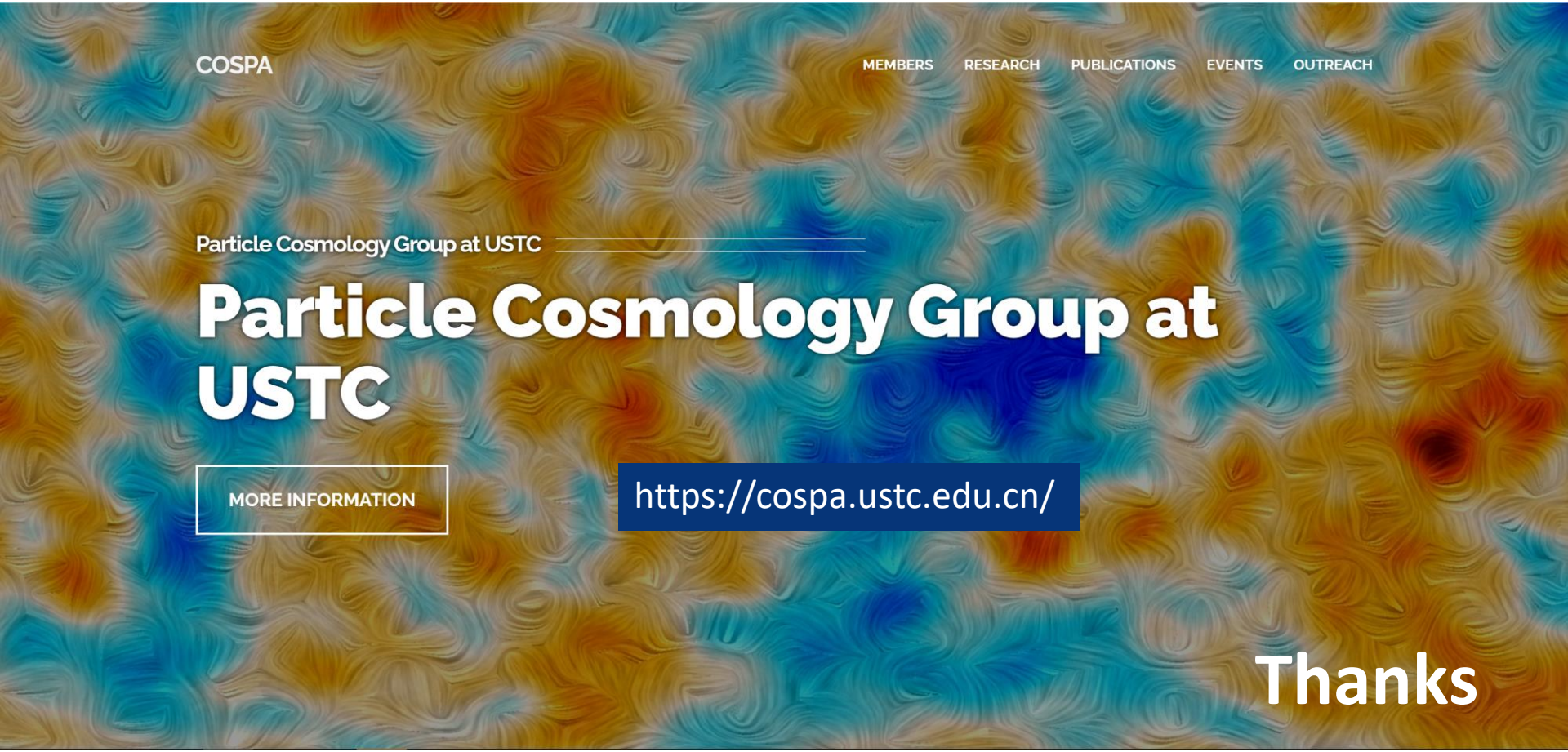
Summary

- Our understanding of the dynamics of late-time cosmic acceleration remains unclear.

- DESI 2024 data interpretation:
  - w(z) exhibits a quintom-B behavior, crossing -1 from phantom region to quintessence region.
  - Modified gravity theory such as metric-affine gravity can explain such a behavior.

- Outlook: Accumulated high-precision data are expected to explore the nature of late-time cosmic acceleration. Also more theoretical mechanisms hold promise for being tested.

- **DESI may shed light on the dynamical nature, more are coming.**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Thanks

The Nobel Prize in Physics 2011

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Saul Perlmutter

Prize share: 1/2

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Brian P. Schmidt

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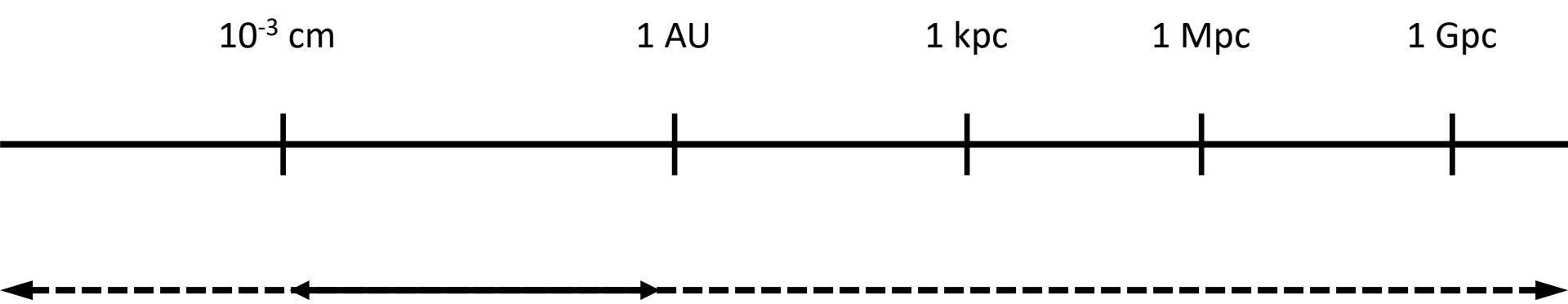
Adam G. Riess

Prize share: 1/4

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

What we know about gravity

Einstein's GR has been precisely probed here



Extra dimensions

MOND

Cosmological Modified gravity

Summary I

- Our understanding of the dynamics of late-time cosmic acceleration remains unclear

- Dark energy physics:
  - A dynamical model is phenomenologically interesting and marginally indicated by observations
  - The precise measurement of the equation-of-state parameter is crucial in examining the nature of DE
  - A proof of theoretical No-Go makes the DE study become phenomenologically fruitful
  - Cosmological tension on H_0

Summary II

- DESI 2024 data interpretation:
  - We use Gaussian process, a nearly “model-independent” way, to quickly and correctly capture the dynamical characteristic of dark energy.
  - w(z) exhibits a quintom-B behavior, crossing -1 from phantom region to quintessence region.
  - Modified gravity theory such as metric-affine gravity can explain such a behavior.
  - For all cases, the quadratic deviation from ΛCDM is mildly favored.

- Outlook: Accumulated high-precision data are expected to explore the nature of late-time cosmic acceleration. Also more theoretical mechanisms hold promise for being tested.

- **DESI may shed light on the dynamical nature, more are coming.**

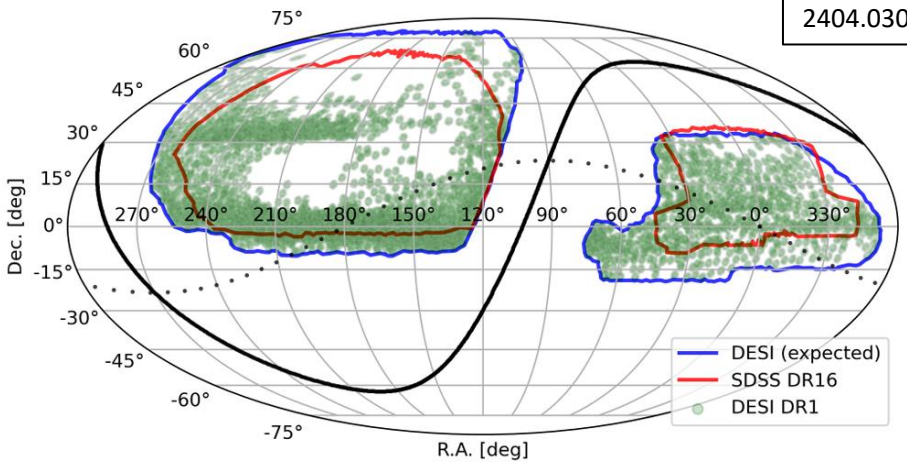
Dark Energy Spectroscopic Instrument

- **Installed on 4-meter Mayall Telescope in Arizona:**
  - Upgraded telescope for wide-field spectroscopy
  - Dedicated to multi-object spectroscopy
- **First Stage-IV Dark Energy Experiment**
  - Optimized for BAO measurements
  - 10X improvement to w_0-w_a posterior area compared to Stage-II Type Ia supernovae measurements
- **Comprehensive cosmology program**
  - Redshift space distortions
  - Cross-correlations with other surveys
  - More cosmology, galaxy evolution, and astrophysics

How is DESI BAO analysis different?

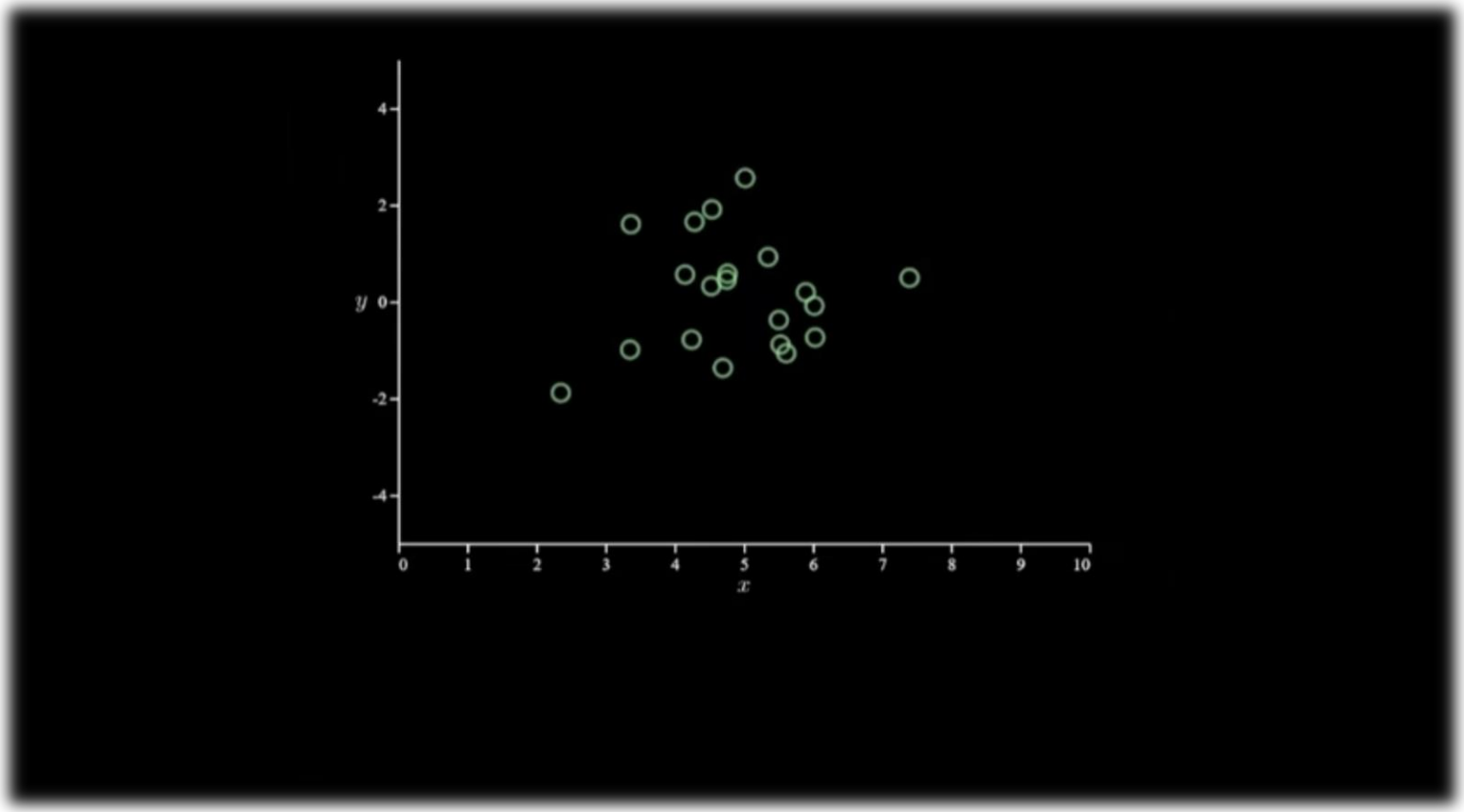
- The biggest data set both in terms of the number and the volume.
- First time a catalog-level blinded BAO analysis to mitigate the confirmation bias.
- Almost all systematics and the baseline methods are determined before unblinding.
- A new reconstruction method.
- A combined tracer to deal with the tracers over the same redshift range (LRG and ELG 0.8<z<1.1).

DESI Collaboration: A.G. Adame et al., 2024
2404.03000, 2404.03001, 2404.03002



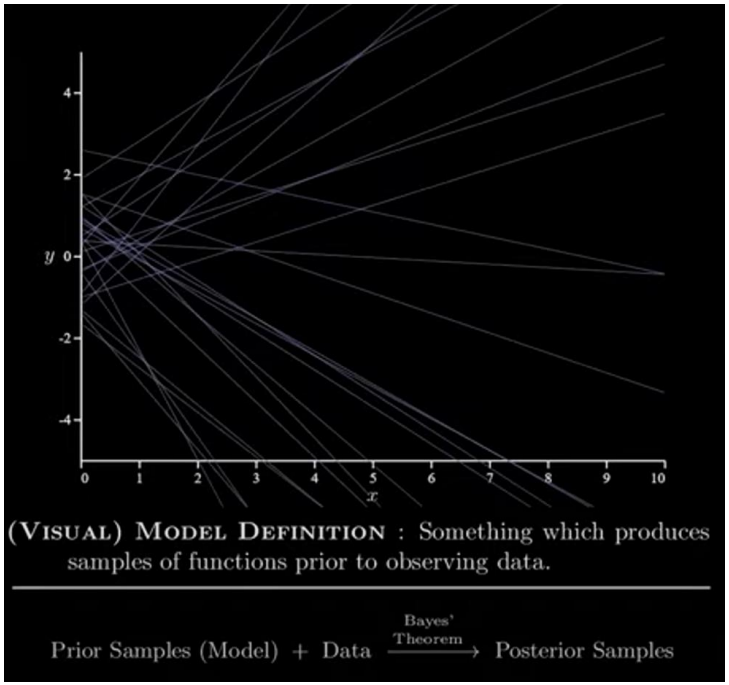
Gaussian Process

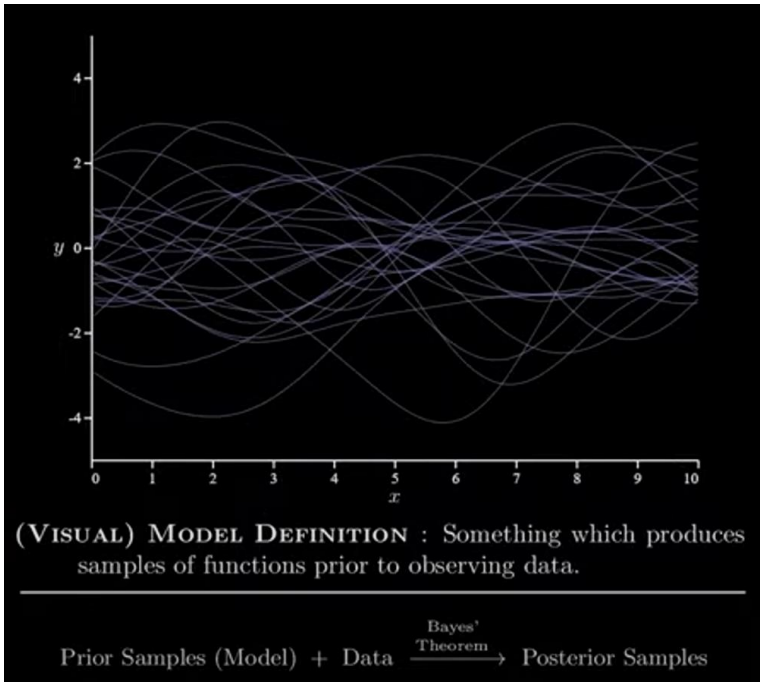
From Bayesian linear regression to Gaussian Process



Gaussian Process

From Bayesian linear regression to Gaussian Process





- Which functions are likely to be sampled are controlled by the kernel function.
- Assume that the distribution functions for the uncertainty are multivariate Gaussian distribution.