PARTICLE COSMOLOGY GROUP
at the University of Science and Technology of China

Exploring the Quintom Dynamics of Late-time Cosmic Acceleration in light of DESI 2024

on Dark Energy & Modified Gravity

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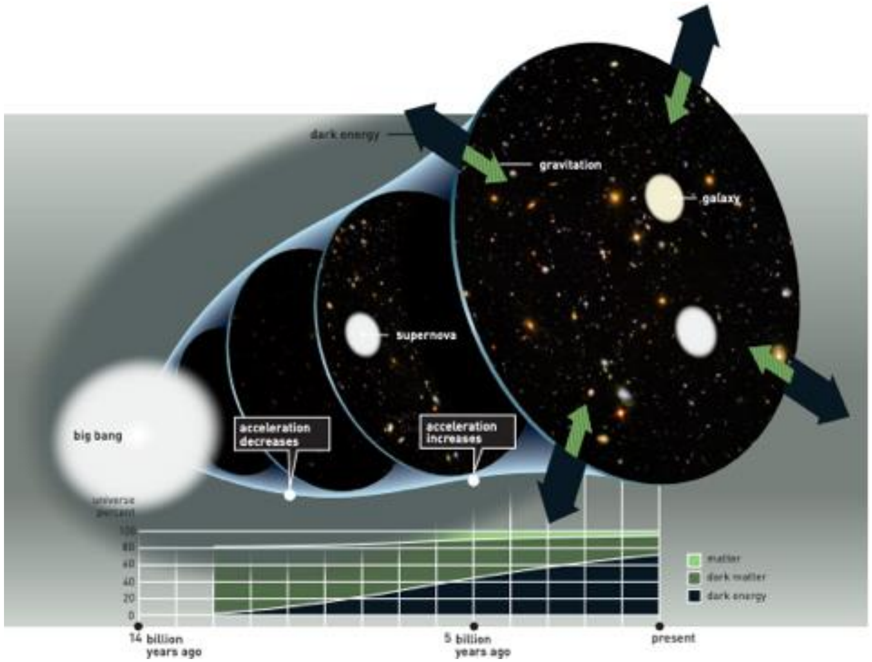
Part 1: Introduction of late-time cosmic acceleration

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.

The Nobel prize in physics 2011

© The Nobel Foundation. Photo: U. Montan

Saul Perlmutter

Prize share: 1/2

© The Nobel Foundation. Photo: U. Montan

Brian P. Schmidt

Prize share: 1/4

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Adam G. Riess

Prize share: 1/4

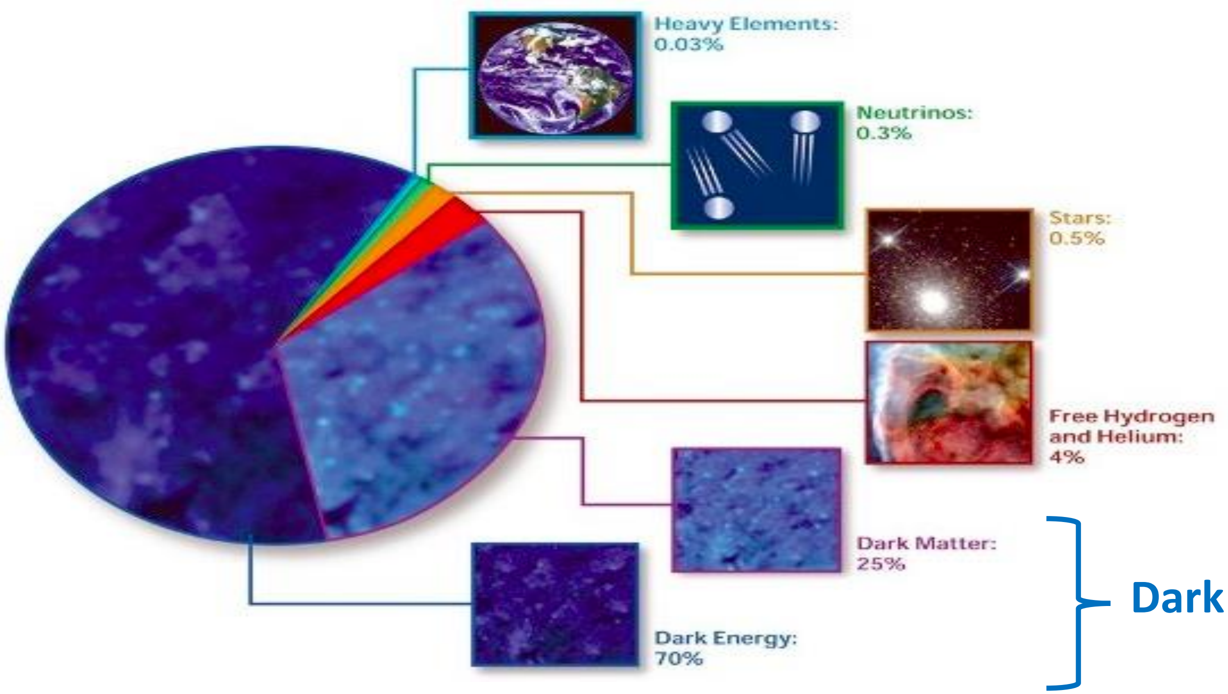
"for the discovery of the **accelerating expansion of the Universe** through observations of distant supernovae."

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



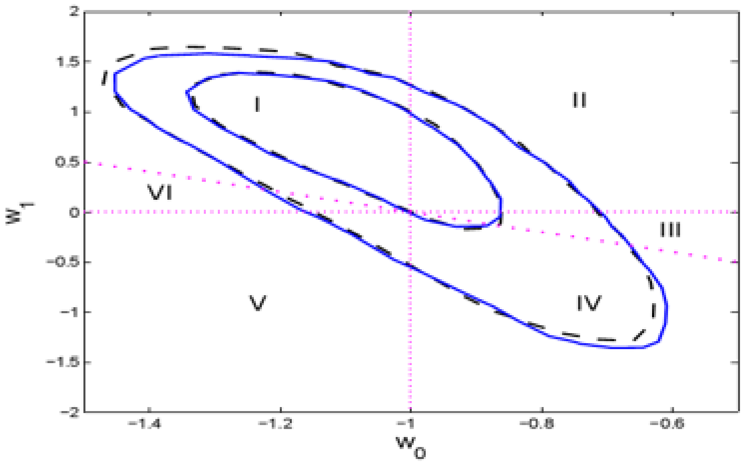
Observable Universe

Dark Universe

Categories of dynamics

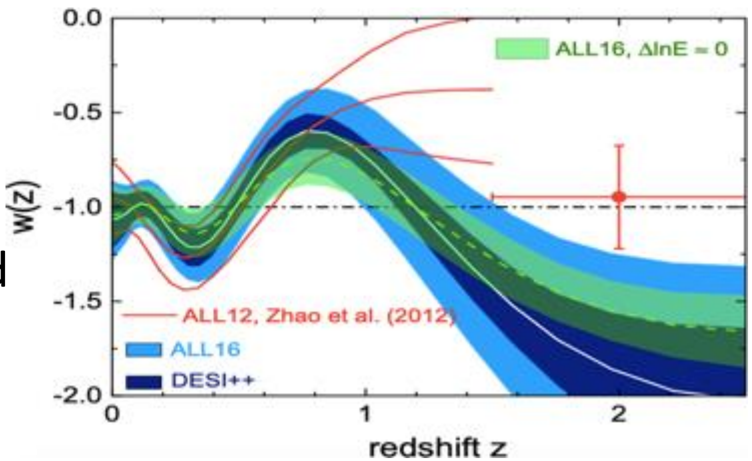
The dynamics of dark energy crucially rely on the equation-of-state parameter, which is defined by the ratio of pressure to energy density

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



Categories:

- Λ: w=-1
- Quintessence: w>-1
- Phantom: w<-1
- Quintom: w crosses -1

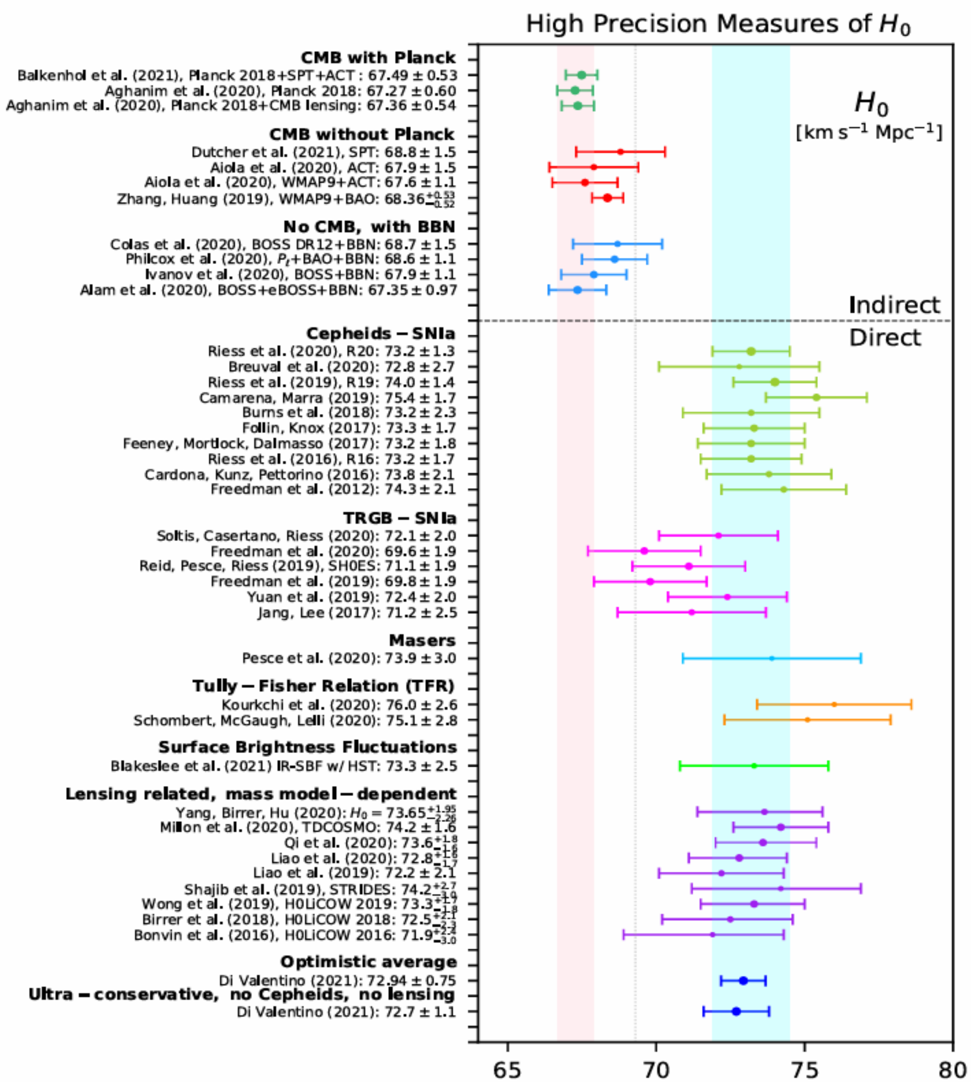


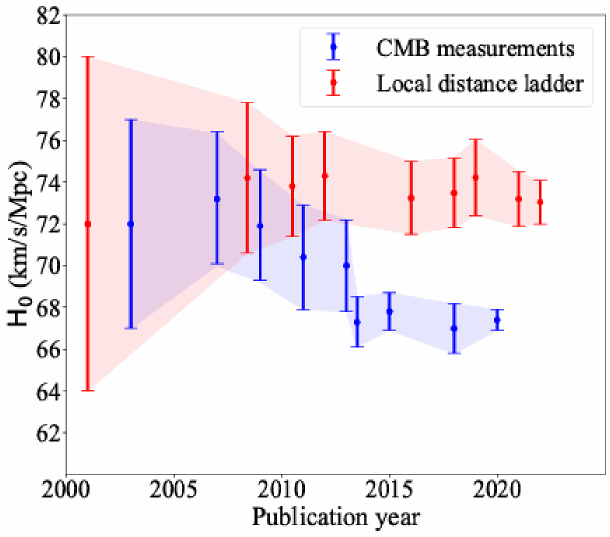
Status:

- Λ is unlikely to address all dynamics
- Dynamical models are marginally favored

Feng, Wang, Zhang, 2004; Huterer, Cooray, 2005; Xia, et al., 2006; Zhao, et al., 2012, 2017

Hubble tension





2018: 3.7σ

2019: 4.4σ

Future: 5σ?

Valentino et al, 2103.01183
Hu et al, 2302.05709

The standard ΛCDM may not be so “standard”!

We need to seek for new physics, namely, modified 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

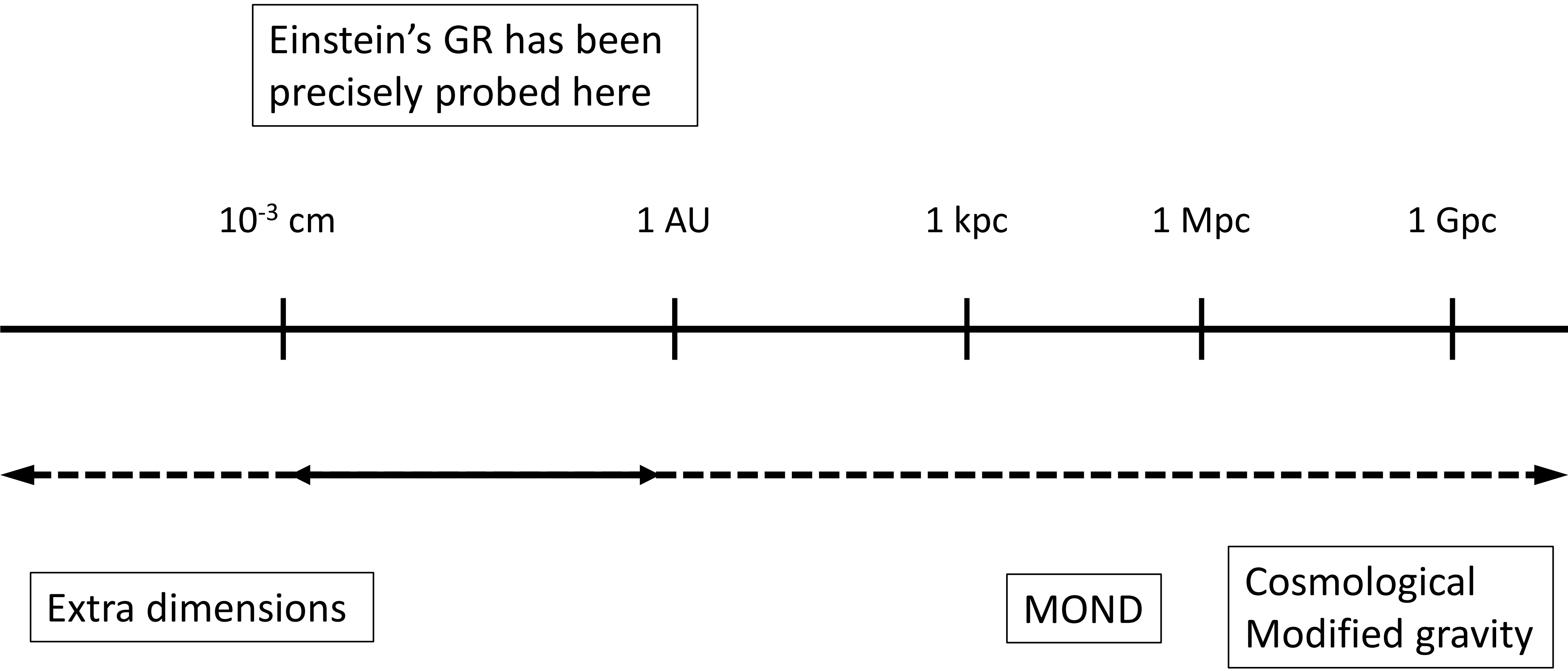
Historical perspective:

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

What we know about gravity



Part 2: DESI BAO 2024

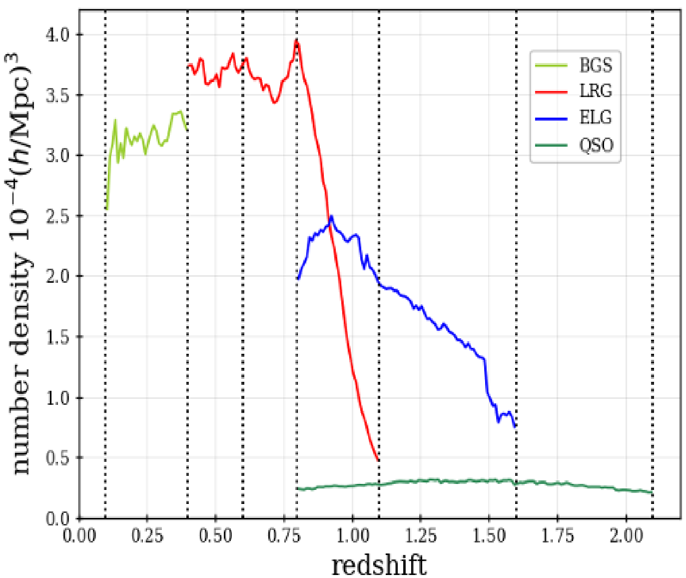
Dark Energy Spectroscopic Instrument

- **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

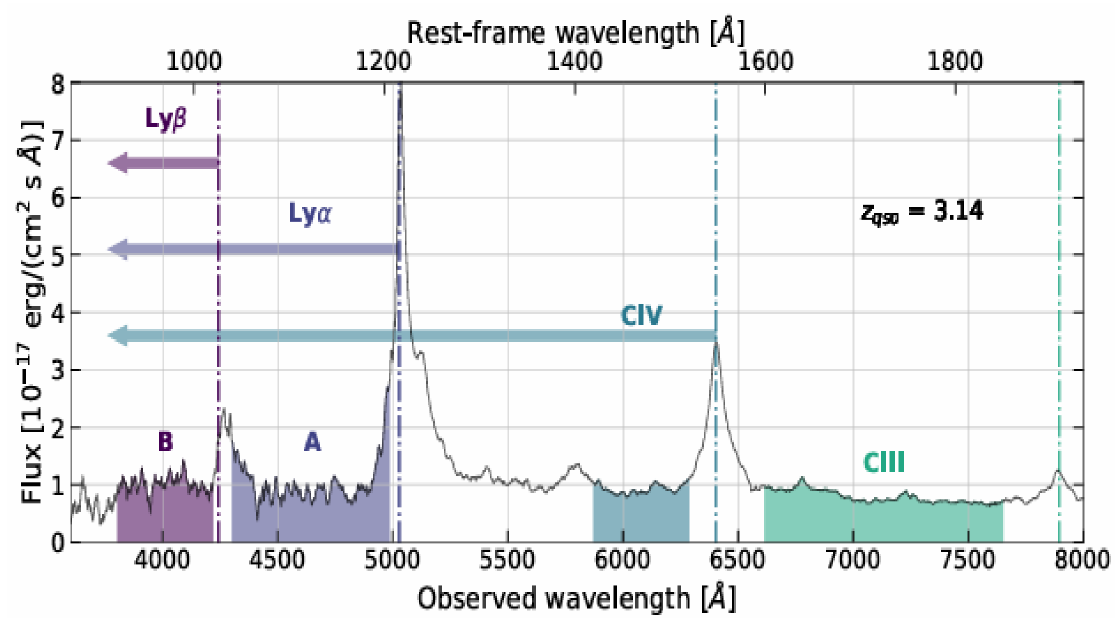
How is DESI BAO analysis different?

- 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.
- Unified BAO framework/pipeline/systematic test on all tracers over a wide redshift range as well as between the Fourier space and the configuration space.
- Physically-motivated enhancements to the BAO fitting method.
- 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 BAO data



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



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

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

Part 3: Cosmological reconstruction and theoretical implications

Based on 2404.19437, accepted by Science Bulletin,
Yang, Ren, Wang, Lu, Zhang, Emmanuel Saridakis & ***CYF***

Gaussian Process

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

Key points：

- The observation data we get are 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.

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

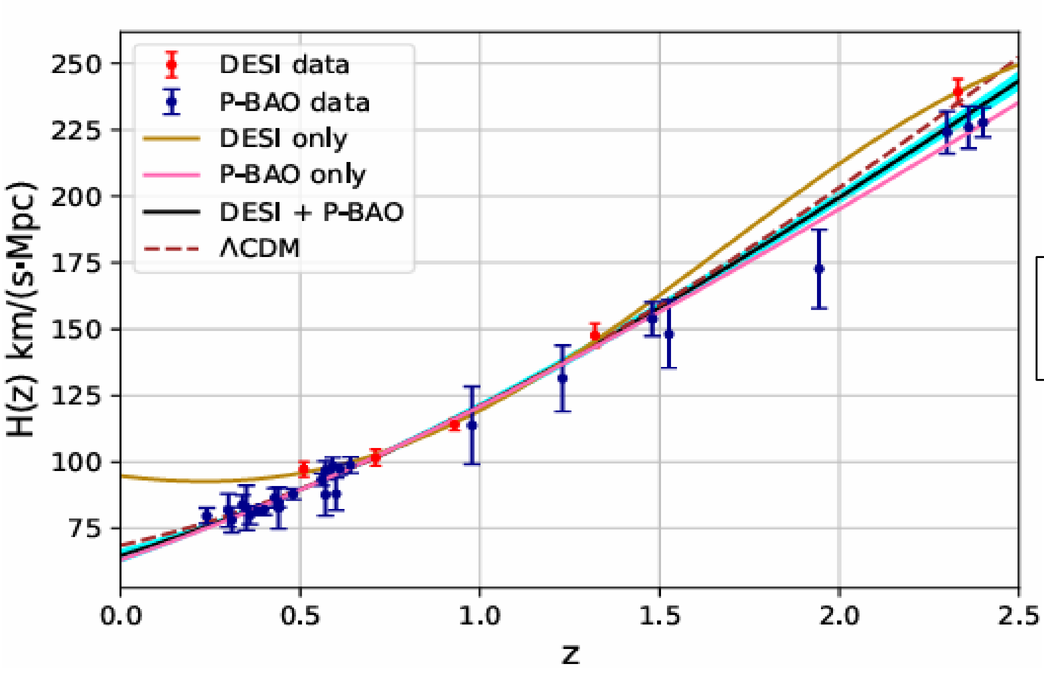
- We apply GAPP (Gaussian Processes in Python) to reconstruct H(z) and its derivatives through observational data points.

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.



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

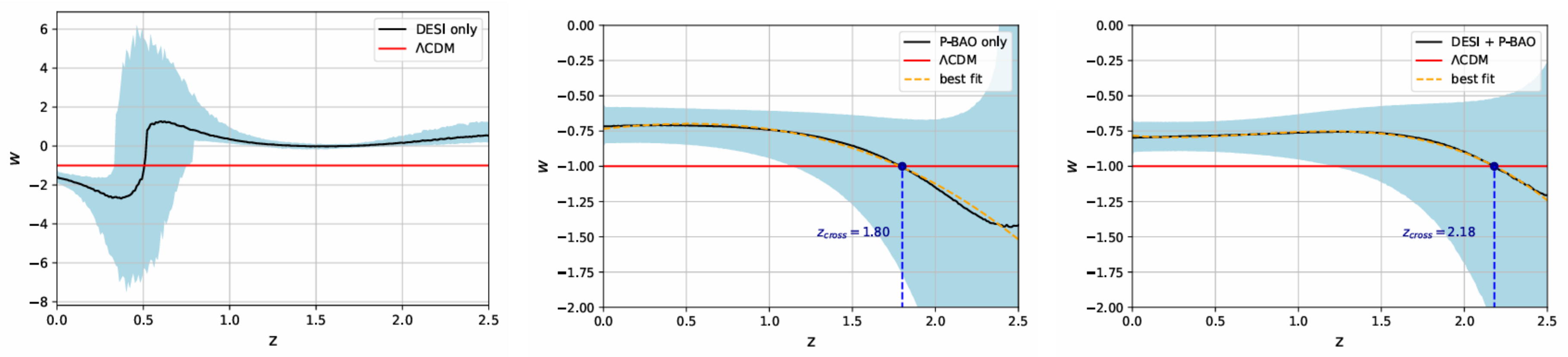
Reconstruction of w(z)

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

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

CYF, 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.



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

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.

Will the confidence of the quintom become larger in the future?

New Dark Energy Tension?

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., 2004; 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

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

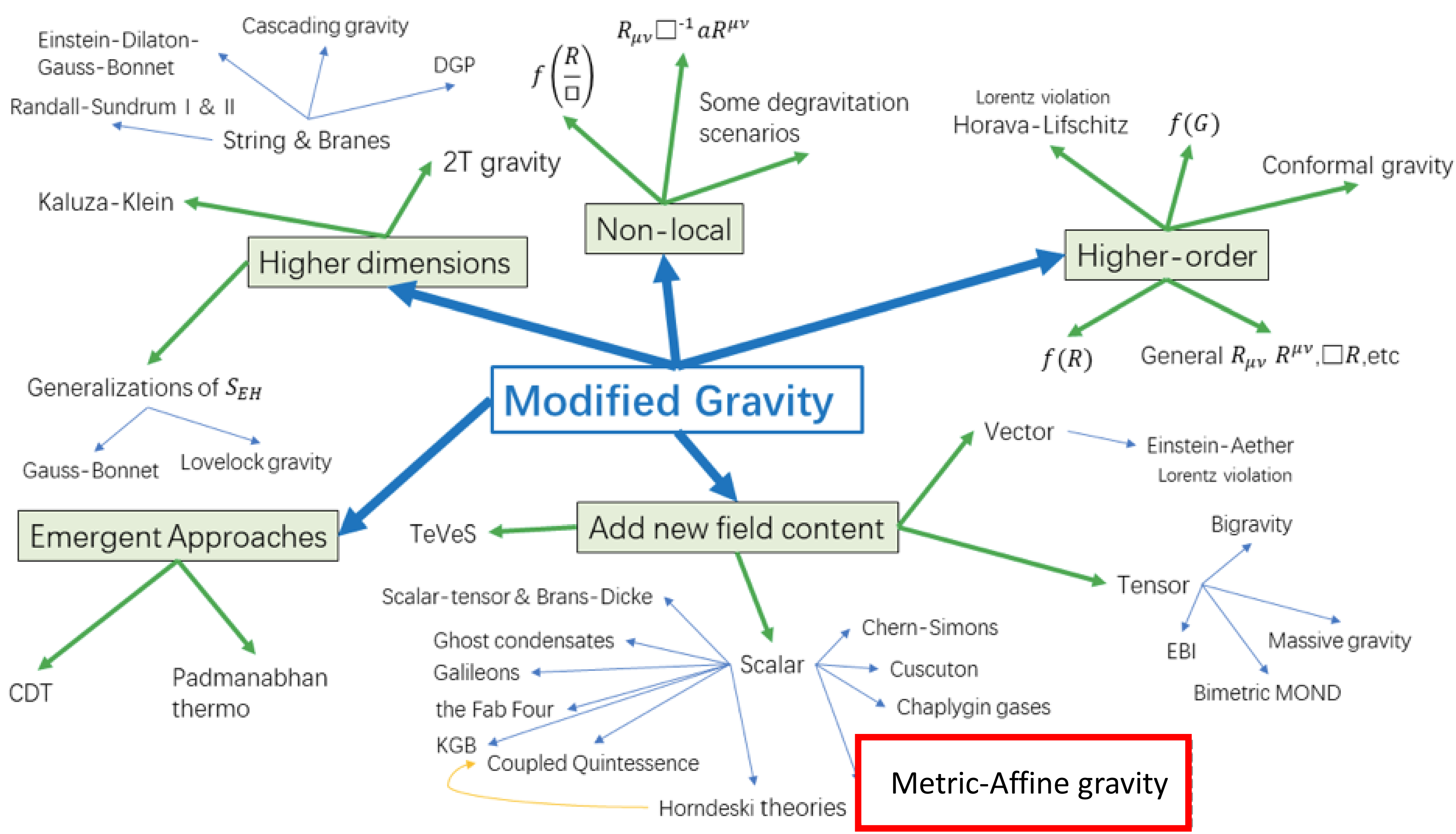
Model Buildings

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
- Theories of modified gravity
- ……

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
Generalizations of S_{EH}
Gauss-Bonnet
Lovelock gravity
$f\left(\frac{R}{\Box}\right)$
$R_{\mu\nu}\Box^{-1}aR^{\mu\nu}$
Some degravitation scenarios
Lorentz violation
Horava-Lifschitz
$f(G)$
Conformal gravity
$f(R)$
General $R_{\mu\nu}$ $R^{\mu\nu}$,$\Box R$,etc
Vector
Einstein-Aether
Lorentz violation
Bigravity
Tensor
EBI
Massive gravity
Bimetric MOND
TeVeS
CDT
Padmanabhan thermo
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Scalar
Chern-Simons
Cuscuton
Chaplygin gases
Metric-Affine gravity

Metric-Affine gravity

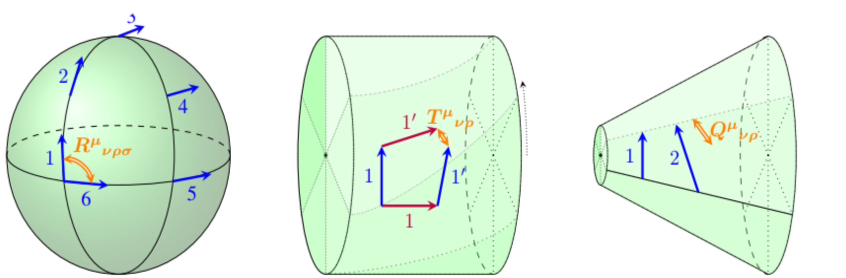
- **Metric-Affine gravity**
  - **f(R)** gravity —— curvature
  - **f(T)** gravity —— torsion
  - **f(Q)** gravity —— non-metricity

(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

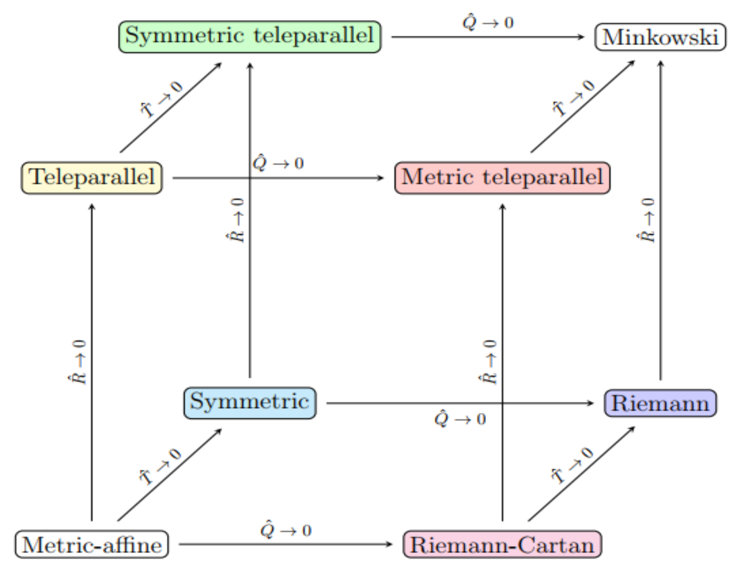
$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}f(X) + \mathcal{L}_m\right] ,$$



curvature torsion non-metricity

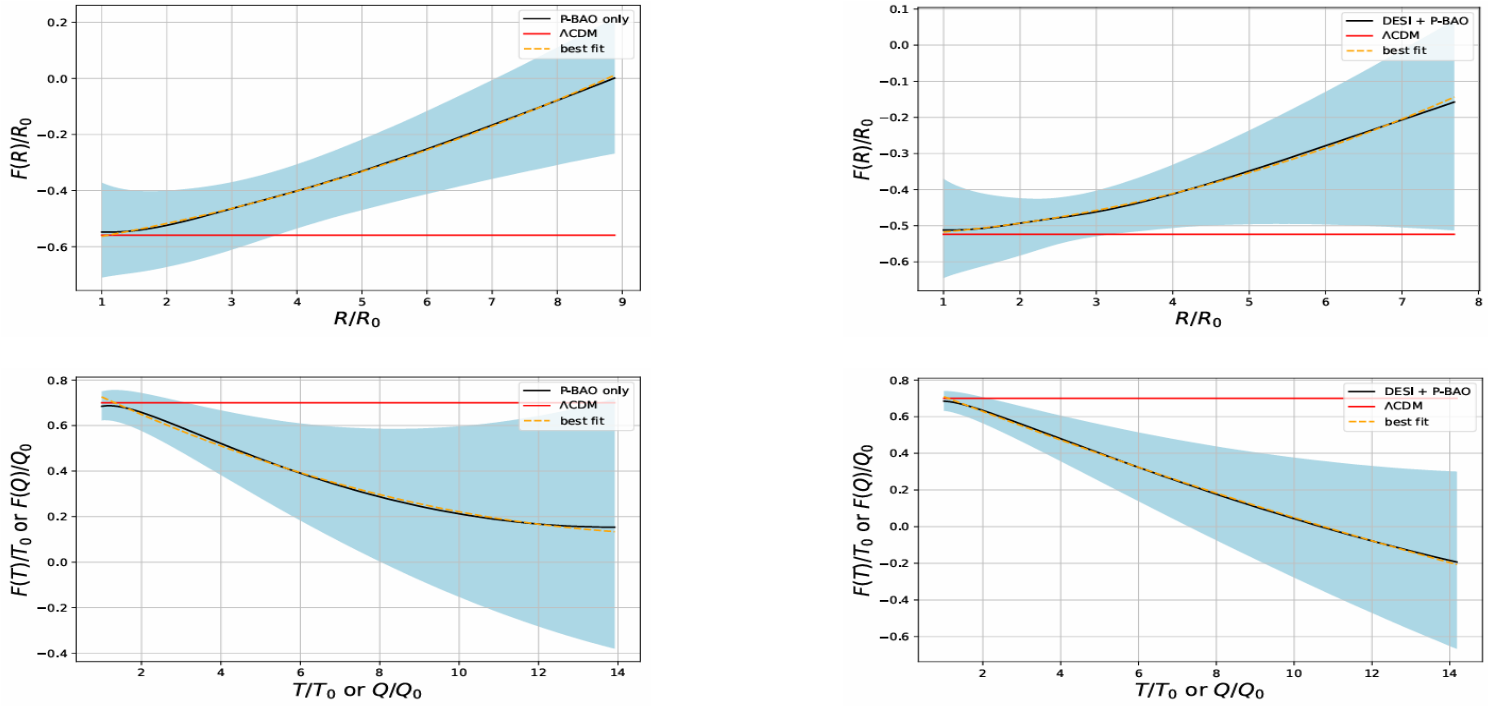
Spacetime geometries

Sebastian Bahamonde et al., 2023



Metric-Affine spacetime

Gravitational interpretations



The reconstructed f(X) can be parametrized as

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

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

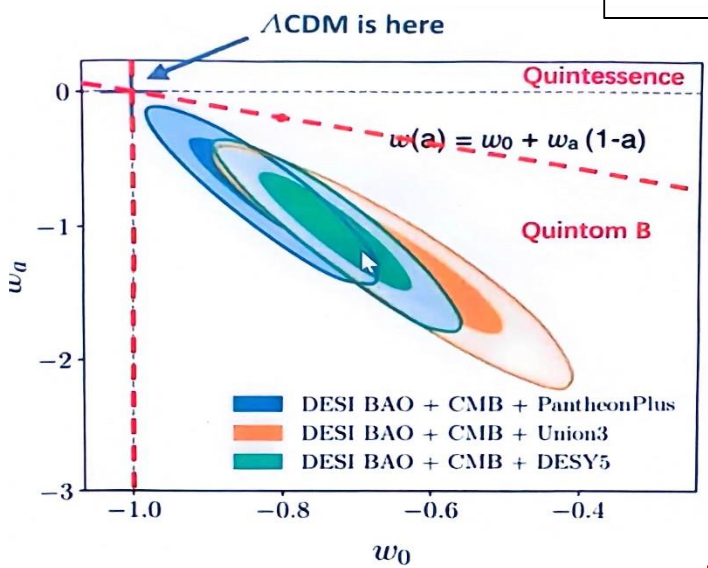
CYF, et al., 2404.19437; Escamilla-Rivera, Sandoval-Orozco, 2405.00608

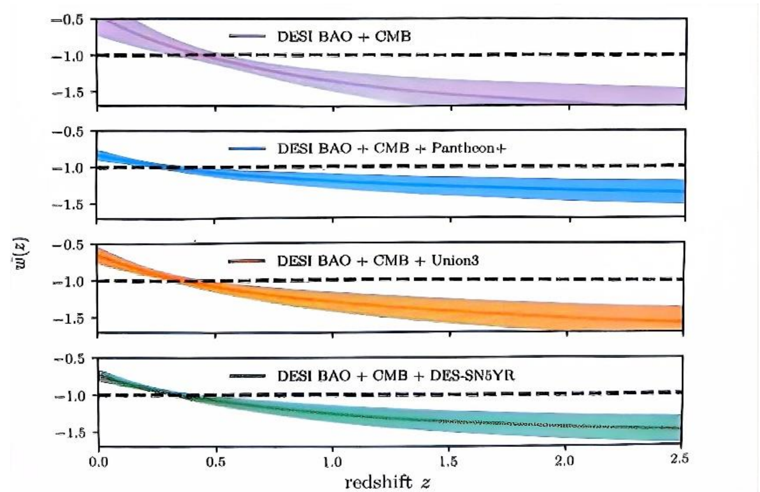
Comment: These are simple examples to illustrate quintom scenario. Our work fosters a bridge for future precise observations and theoretical mechanisms.

How is our analysis different?

w_0-w_a parametrization:

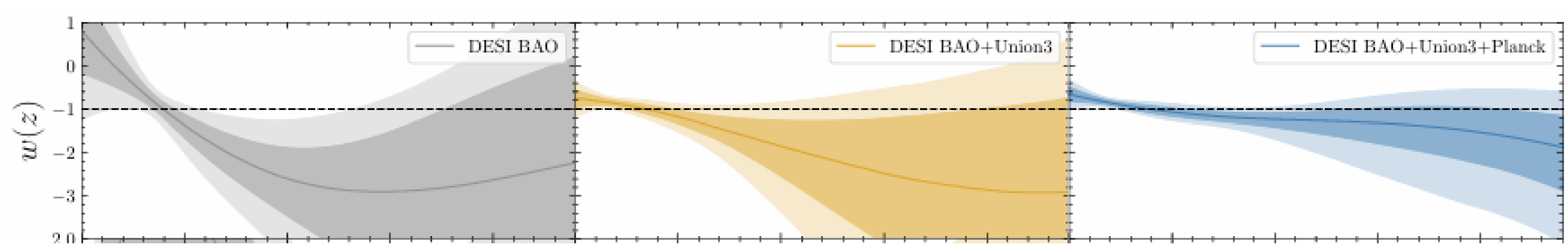
Marina et.al. 2404.08056, DESI Collaboration, Calderon et.al. 2405.04216





Chebyshev expansion:

All quintom-B!



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

Part 4: Conclusion and discussion

Summary I

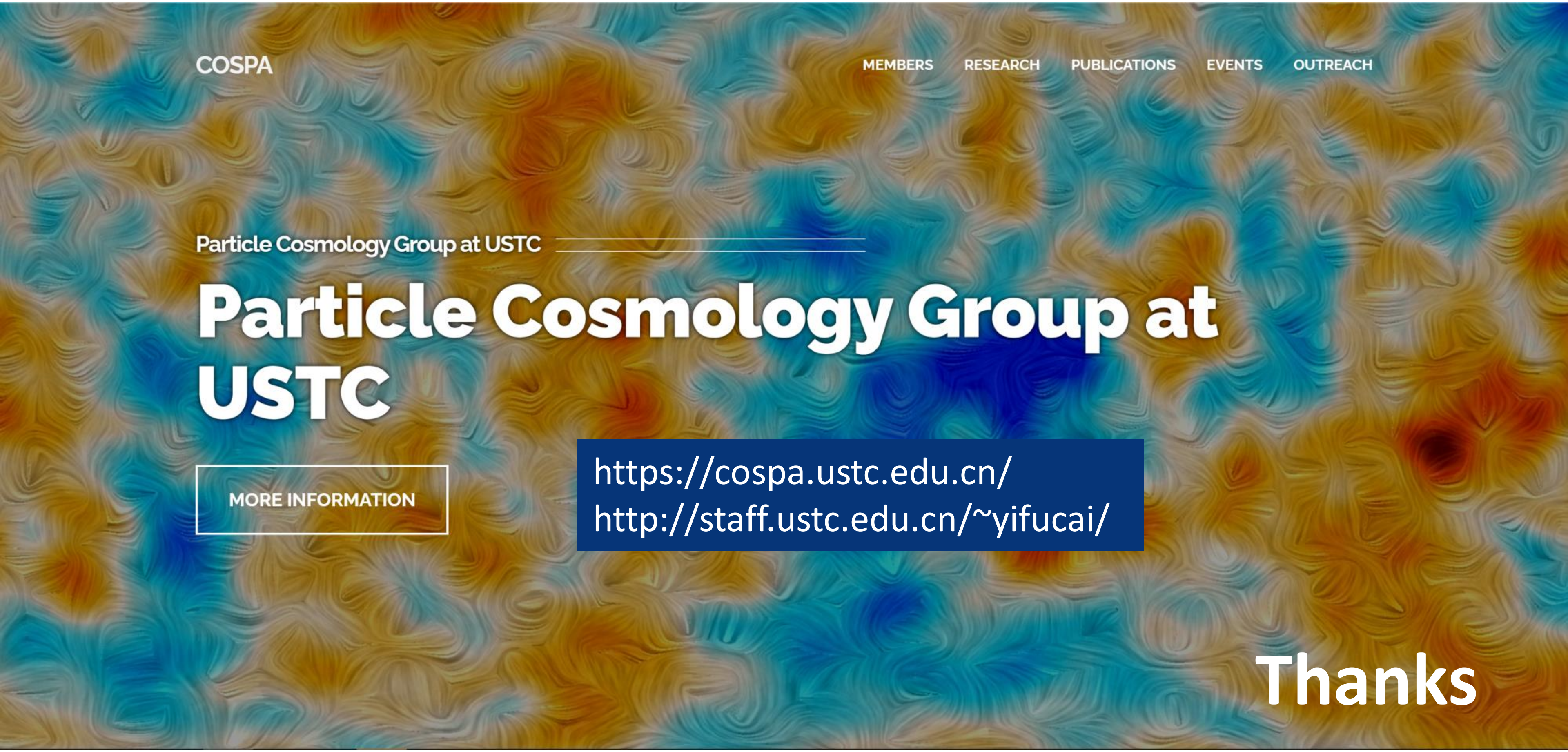
- Our understanding of the dynamics of late-time cosmic acceleration remains unclear

- 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(s) on the Hubble diagram

Summary II

- DESI 2024 data interpretation:
  - We use Gaussian process, a nearly "model-independent" way, to quickly capture the dynamical characteristic of dark energy;
  - w(z) exhibits a quintom-B behavior, crossing -1 from phantom to quintessence;
  - Modified gravity such as metric-affine gravity can be an example to illustrate such a behavior;
  - For all cases, the quadratic deviation from ΛCDM looks mildly favored.

- Outlook:
  - Accumulated high-precision data are expected to explore the nature of late-time cosmic acceleration, and hence, theoretical models hold promise for being falsified;
  - **DESI shed light on the dynamical nature, more are coming.**



https://cospa.ustc.edu.cn/
http://staff.ustc.edu.cn/~yifucai/

Thanks