基于DESI 最新测量的暗能量研究

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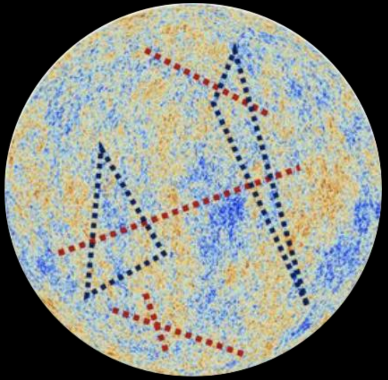
提纲

1. 关键科学问题
2. 最新研究进展
3. 未来巡天计划
4. 总结

关键科学问题

- 原初非高斯性 ($f_{NL} \sim 0$)？
- 原初张量扰动信息 (B-mode信号)？

宇宙早期
加速膨胀

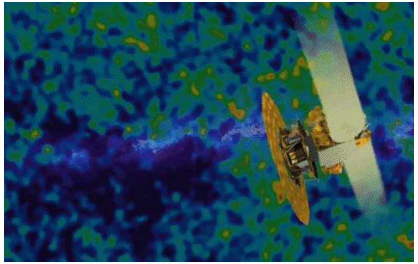


宇宙后期
加速膨胀

- 宇宙学常数还是动力学暗能量?
- GR理论在宇宙学尺度需要修改?

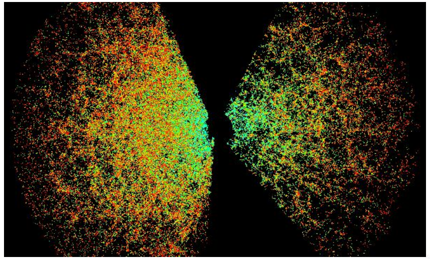
多重宇宙学探针

Ia型
超新星



宇宙微波
背景辐射

LSS-重子
声波振荡

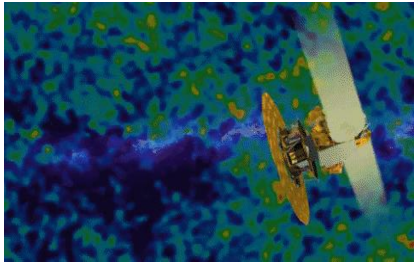


多探针交叉
联合检验

LSS-引力透镜,FRB,引力波,21cm, etc

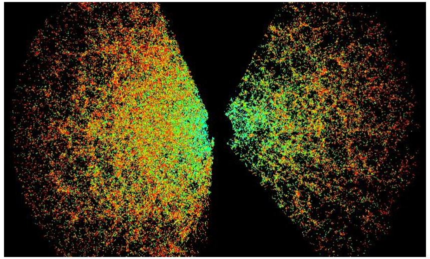
多重宇宙学探针

Ia型超新星



LSS-重子声波振荡

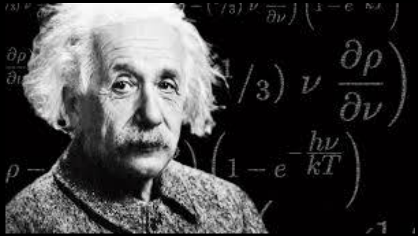
宇宙微波背景辐射



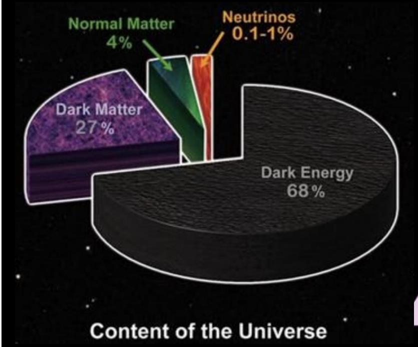
LSS-引力透镜,FRB,引力波,21cm, etc

The Standard Model

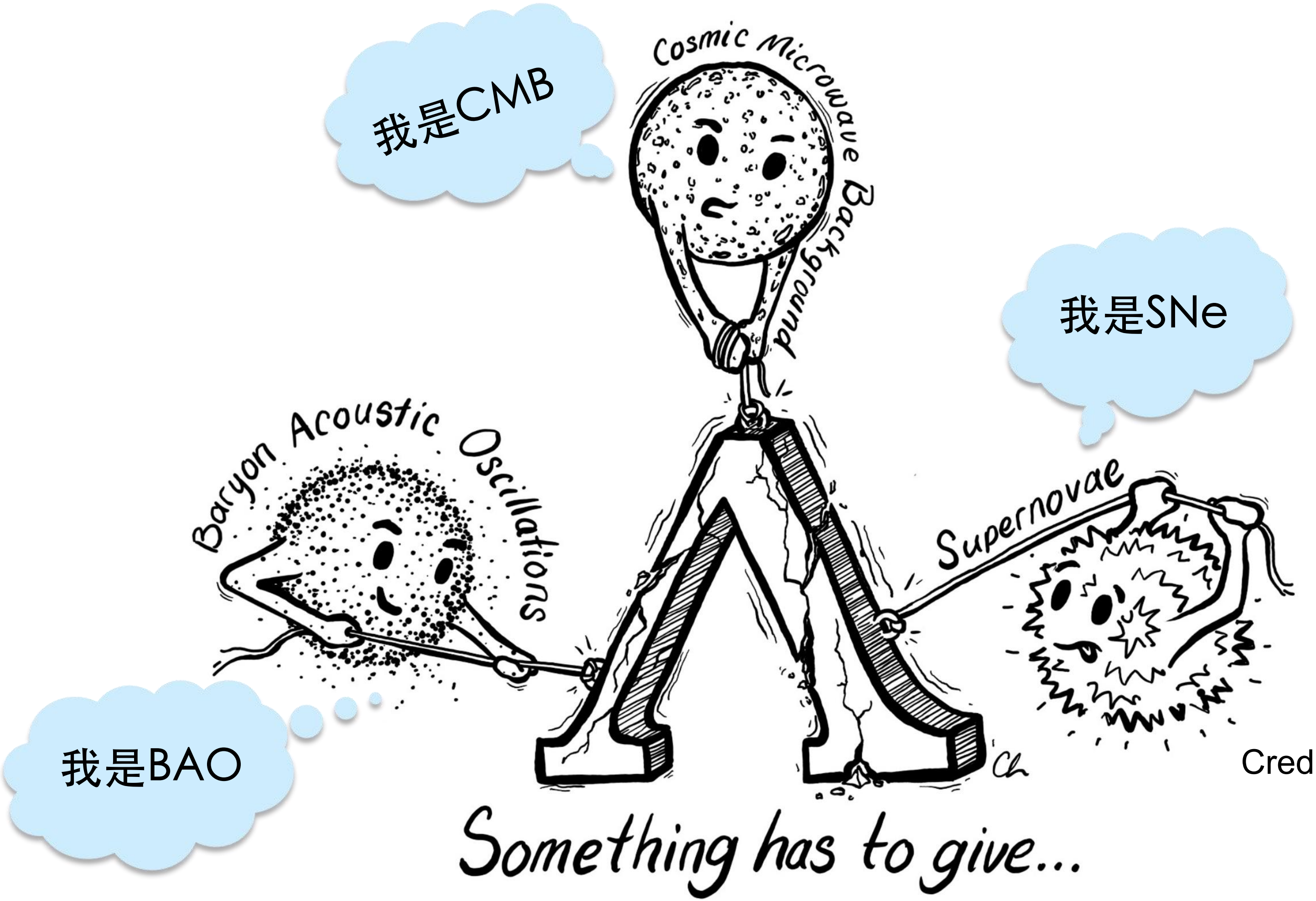
暗能量状态方程 $w = \frac{\text{暗能量压强}}{\text{暗能量密度}}$



$w = -1$

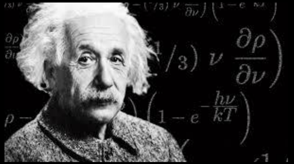


ΛCDM



Credit: Claire Lamman

暗能量状态方程 $w = \dfrac{\text{暗能量压强}}{\text{暗能量密度}}$



真空能暗能量： w = -1 (Einstein, 1917)

“精质”暗能量： w > -1 (Ratra & Peebles, 1988)

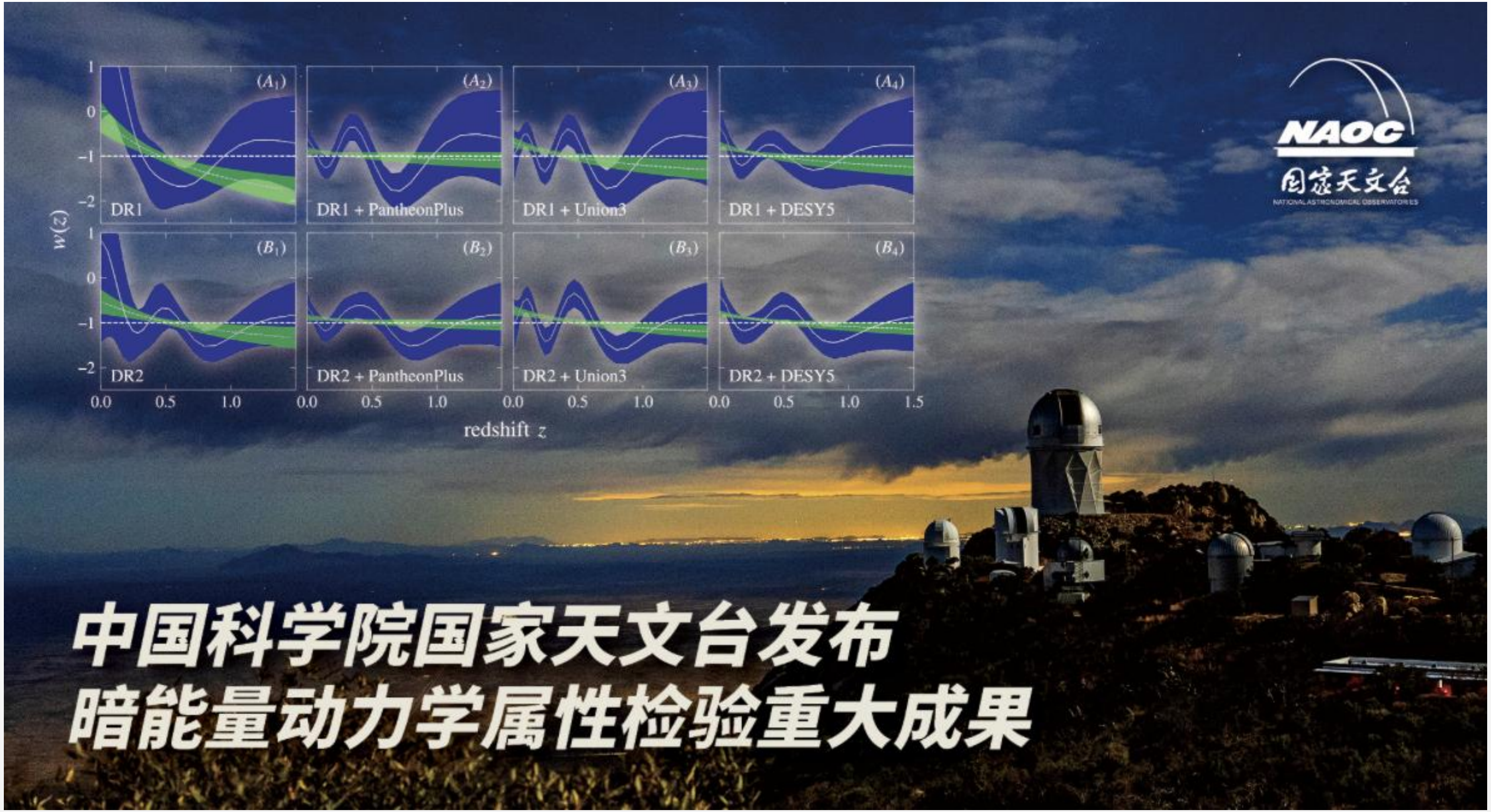
“幽灵”暗能量： w < -1 (Caldwell, 2002)

“精灵”暗能量： w 穿越 -1 (Zhang’s group,2004)

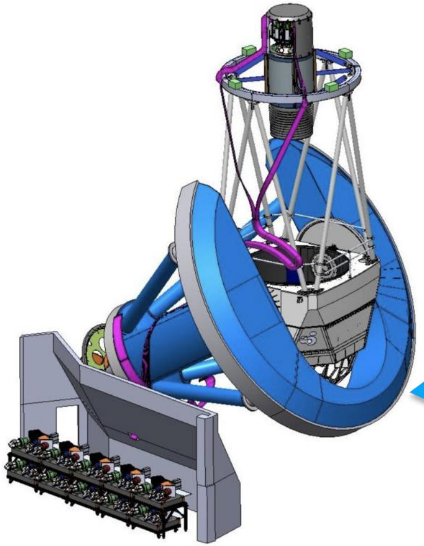
Slide credit: Gong-Bo Zhao

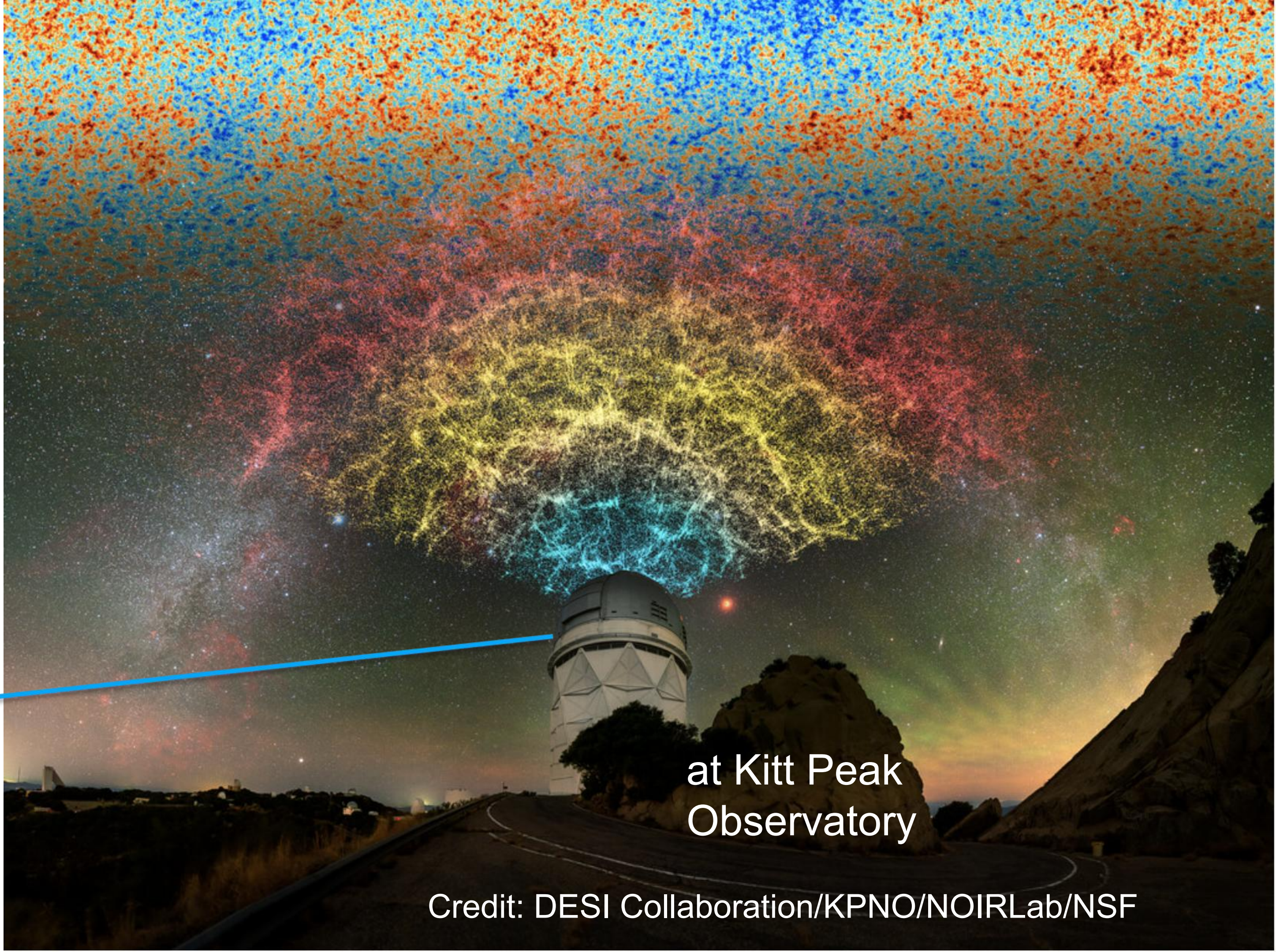
研究成果

Zhao’s group + DESI 合作组, 2025

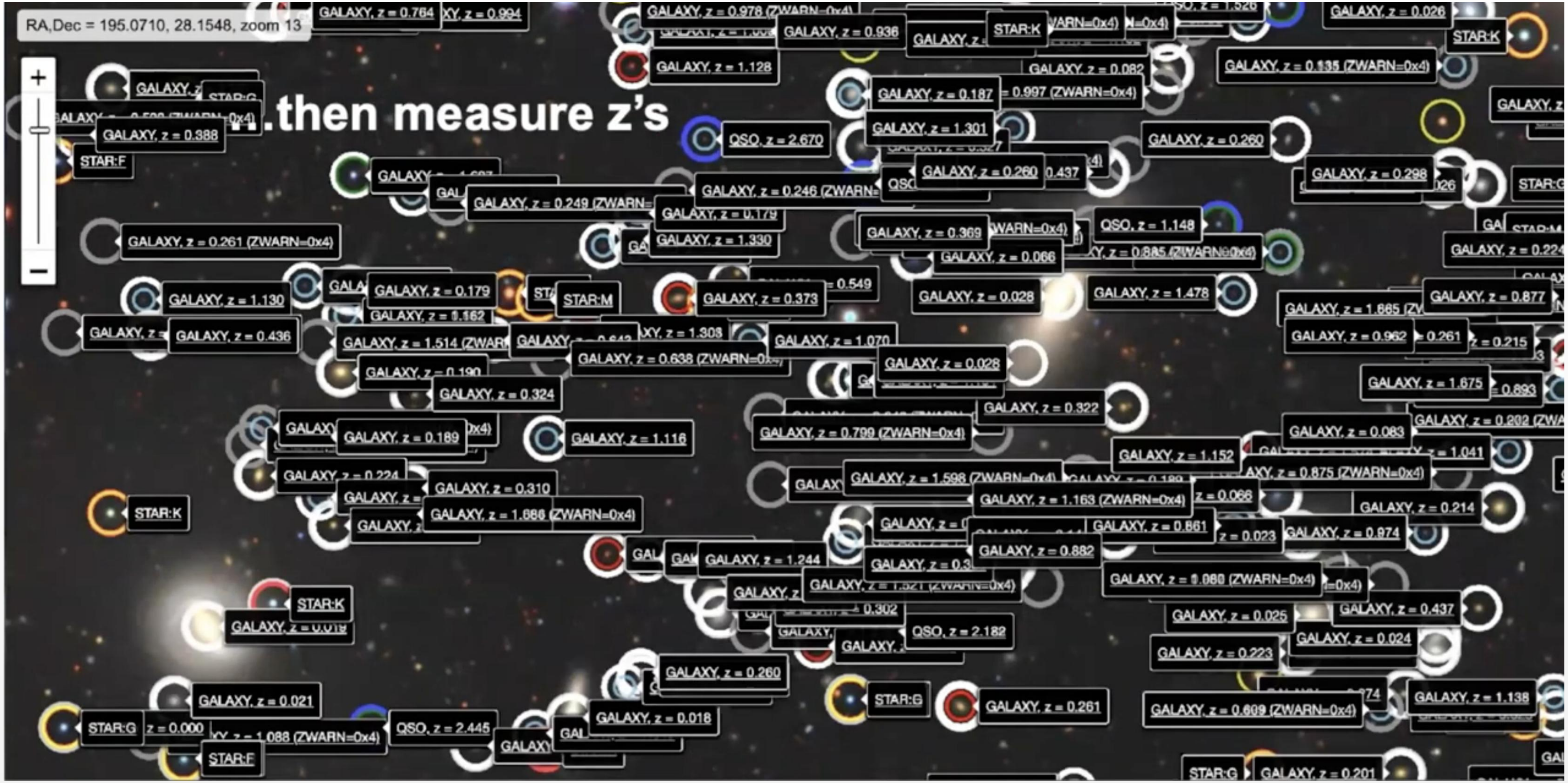


大规模星系巡天
DESI



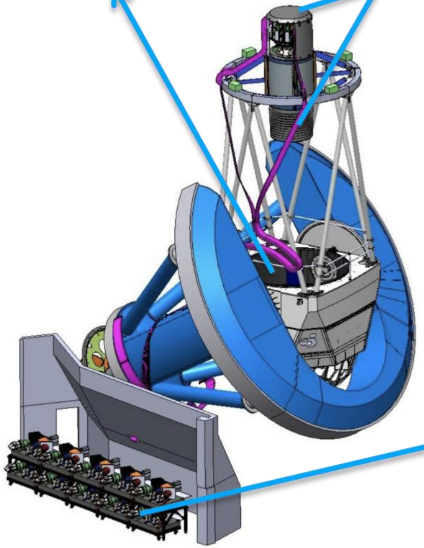


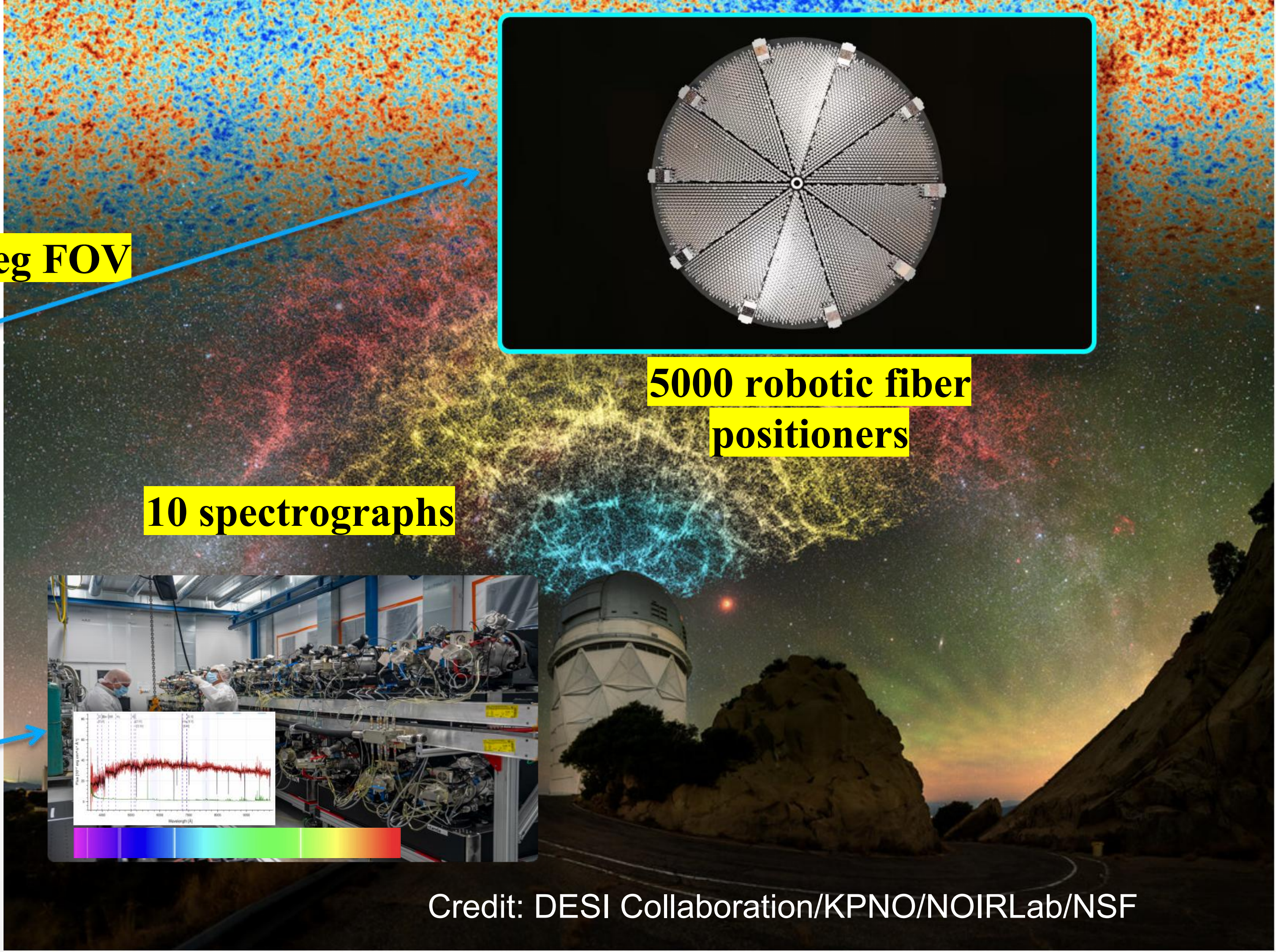
大规模星系巡天 DESI - measure z's



大规模星系巡天

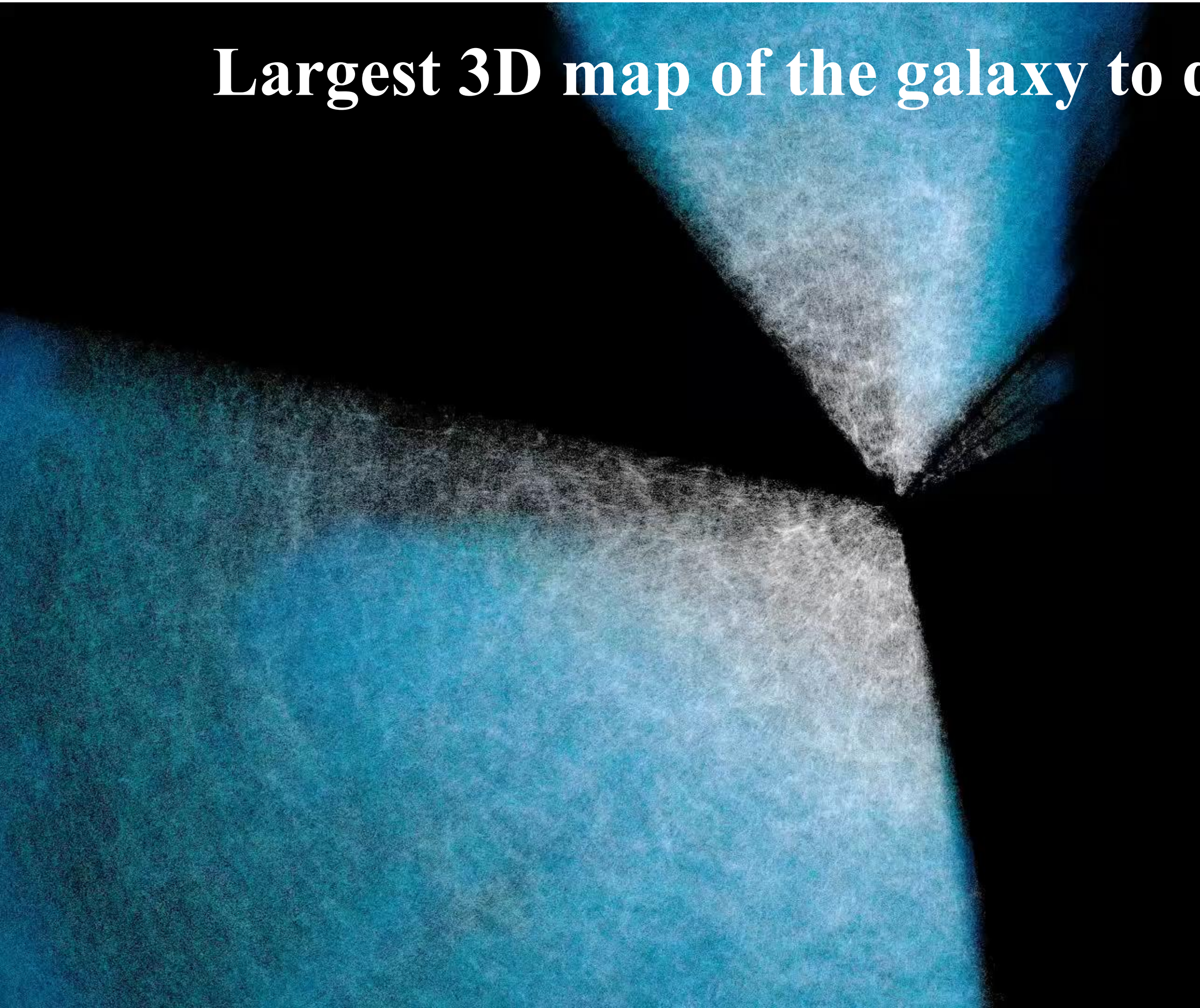
DESI





Credit: DESI Collaboration/KPNO/NOIRLab/NSF

Largest 3D map of the galaxy to date

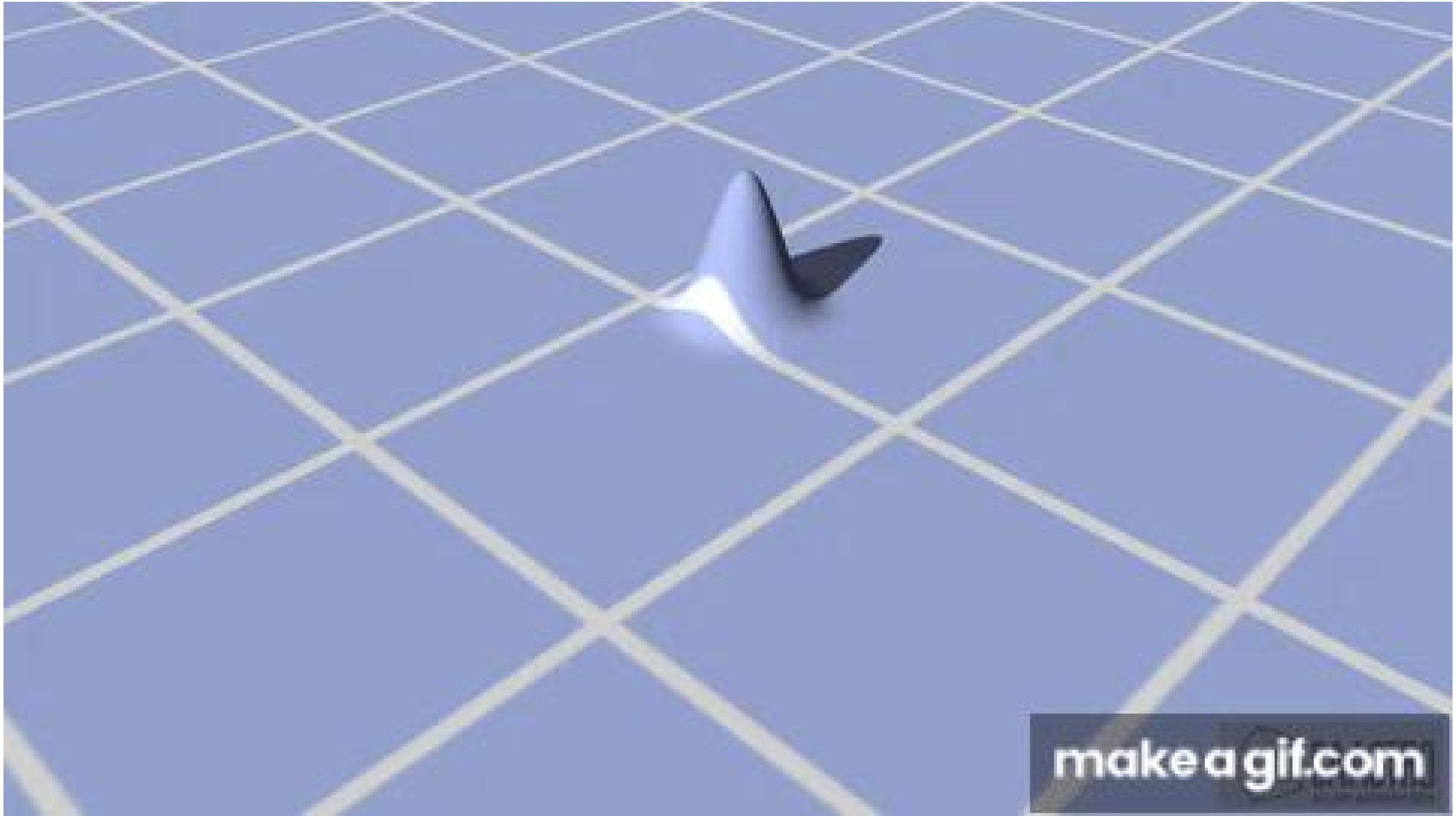


- BGS
- LRG
- ELG
- QSO
- Ly-α

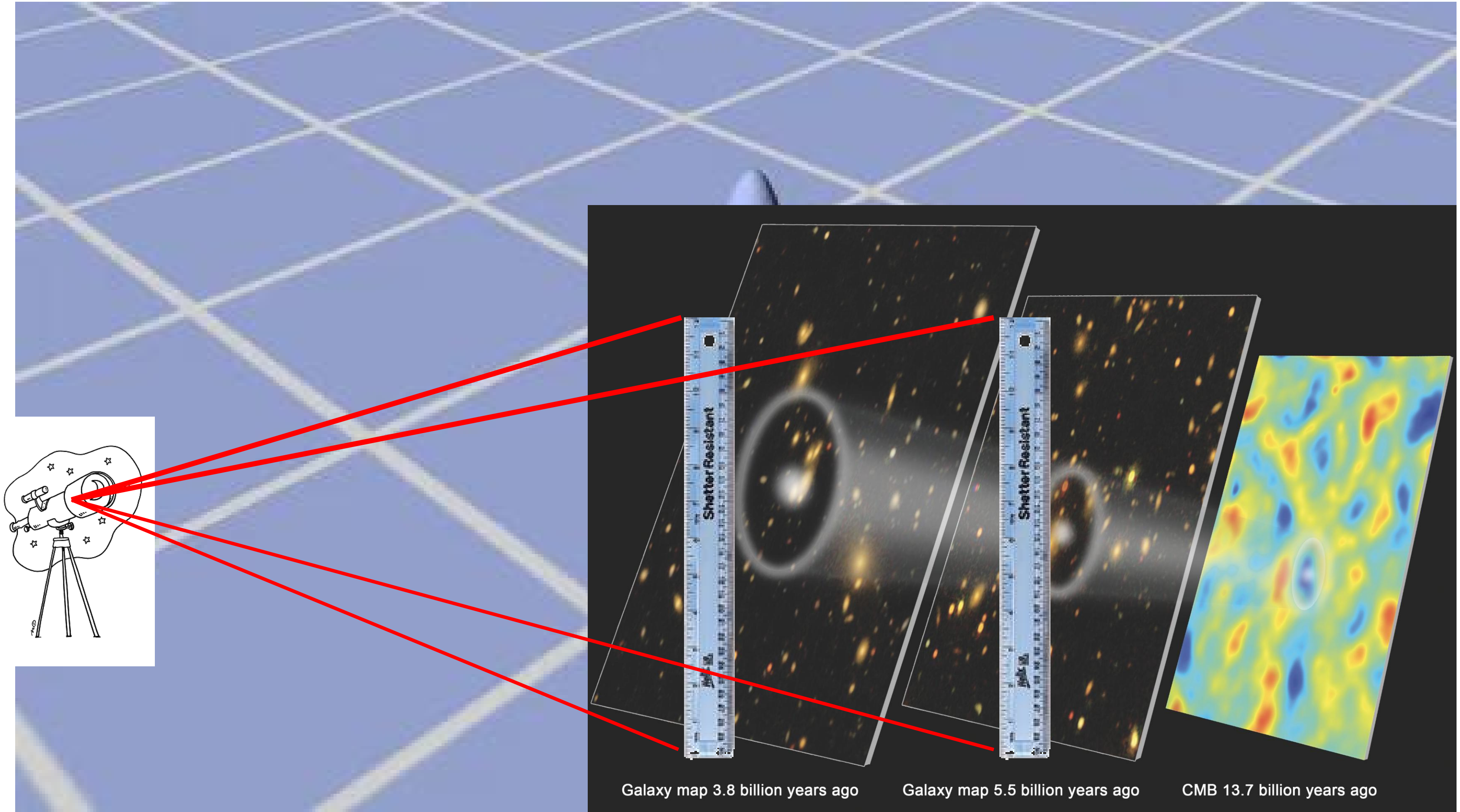
~14M

Credit： DESI合作组

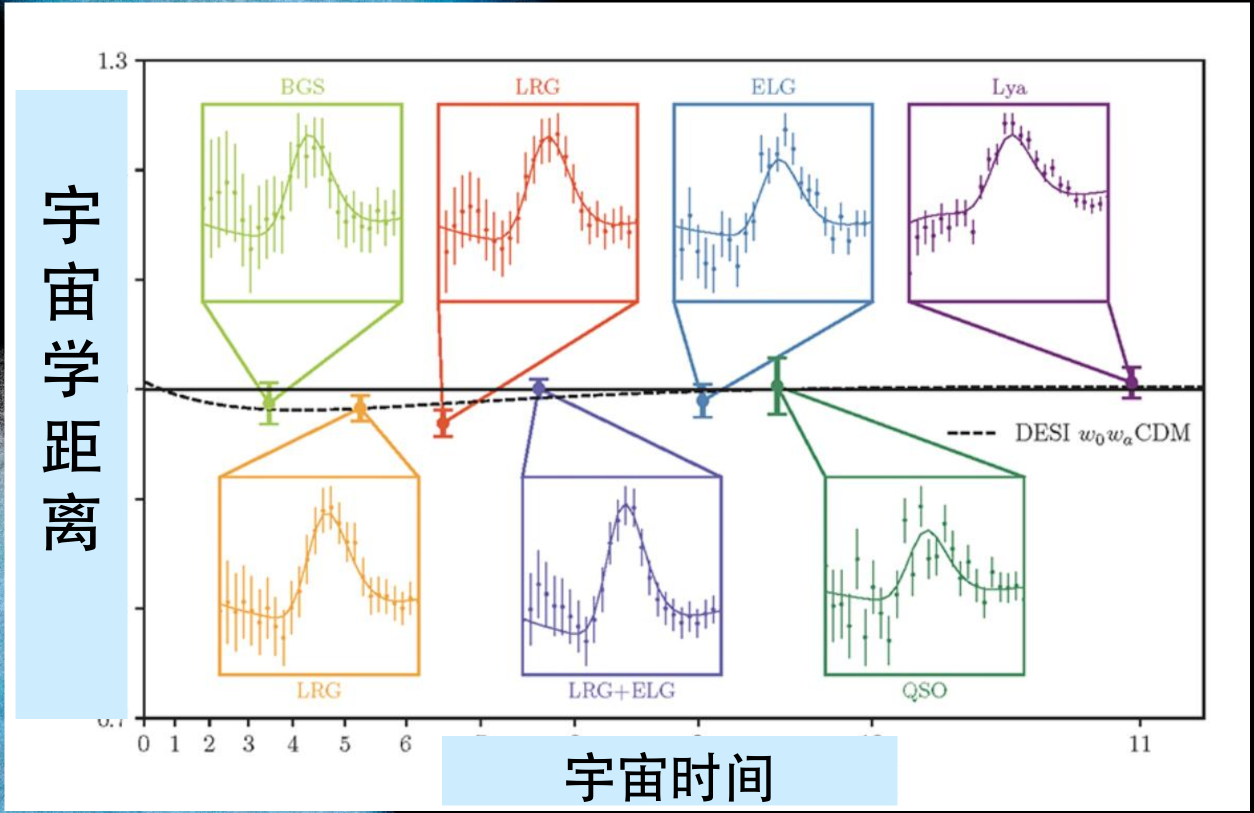
Baryon acoustic oscillations (BAO)



BAO - 宇宙膨胀速率


Shatter Resistant
Shatter Resistant
Galaxy map 3.8 billion years ago
Galaxy map 5.5 billion years ago
CMB 13.7 billion years ago

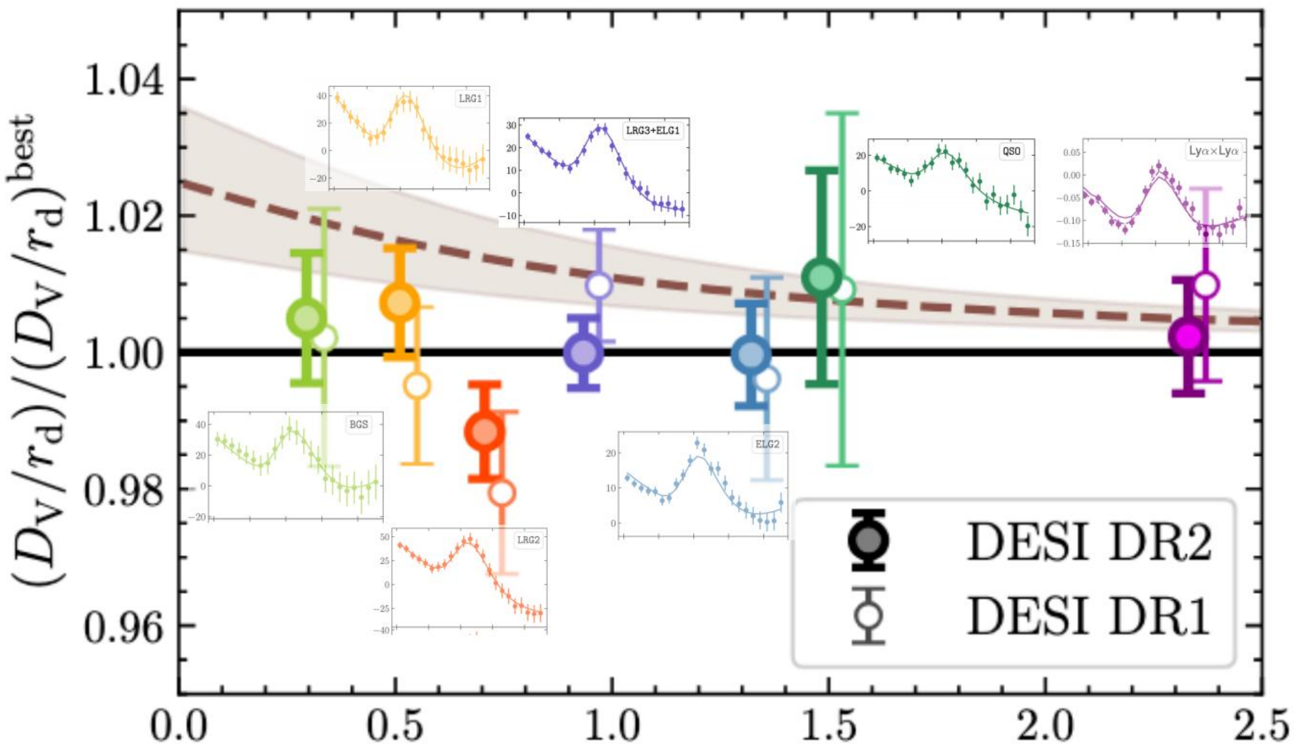
Largest 3D map of the galaxy to date



Credit： DESI合作组

DESI BAO results

宇宙学距离



红移

Two ways to study dynamics of dark energy

- **Indirect: get features of w(z) directly from distance measurements**

✓: cheap; no data combination needed

✗: no w(z) derived

单组数据、定性分析

- **Direct: reconstruct w(z) from observations**

✓: show w(z) with details

✗: expensive; usually requires datasets to be combined

联合数据、定量分析

Gan Gu, Xiaoma Wang, 王钰婷, Gongbo Zhao, +DESI 合作组，arXiv：2504.06118

Probing dynamical DE from distance measurements

(Gu et al, 2404.06303; Wang et al, 2404.06310)

$$\frac{D_{\mathrm{A}}(z)}{D_{\mathrm{A,fid}}(z)} = \alpha_0 \left(1 + \alpha_1 x + \frac{1}{2}\alpha_2 x^2 + \frac{1}{6}\alpha_3 x^3 + \frac{1}{24}\alpha_4 x^4\right)$$

(Zhu et al, 2015)

$$\frac{H_{\mathrm{fid}}(z)}{H(z)} = \alpha_0 \left[1 + \alpha_1 + (2\alpha_1 + \alpha_2)x + \left(\frac{3}{2}\alpha_2 + \frac{1}{2}\alpha_3\right)x^2 + \left(\frac{2}{3}\alpha_3 + \frac{1}{6}\alpha_4\right)x^3 + \frac{5}{24}\alpha_4 x^4\right]$$

$$1 + x \equiv D_{\mathrm{A,fid}}(z)/D_{\mathrm{A,fid}}(z_\star)$$

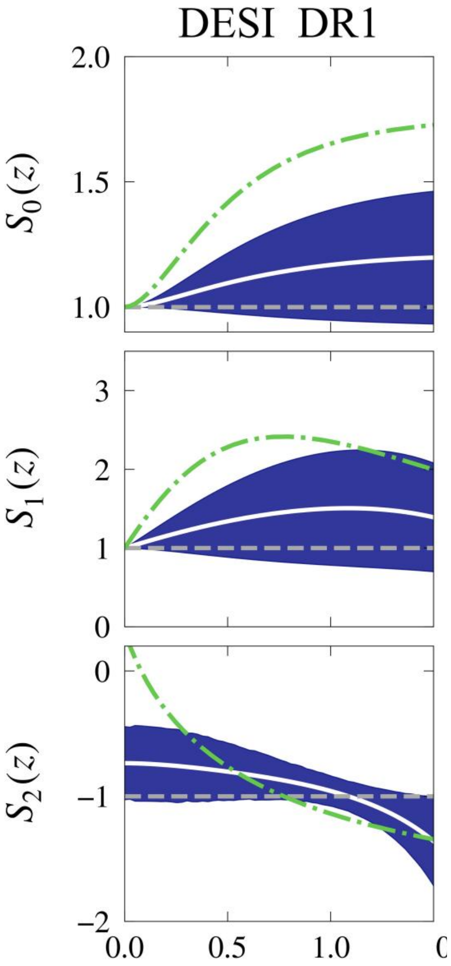
$$S(a) \equiv A\ H^2(a)a^3 = B\ X(a)a^3 + C$$

$$A = r_{\rm d}^2,\ B = AH_0^2(1-\Omega_{\rm M}),\ C = AH_0^2\Omega_{\rm M} \quad X(a) \equiv \rho_{\rm DE}(a)/\rho_{\rm DE}(1)$$

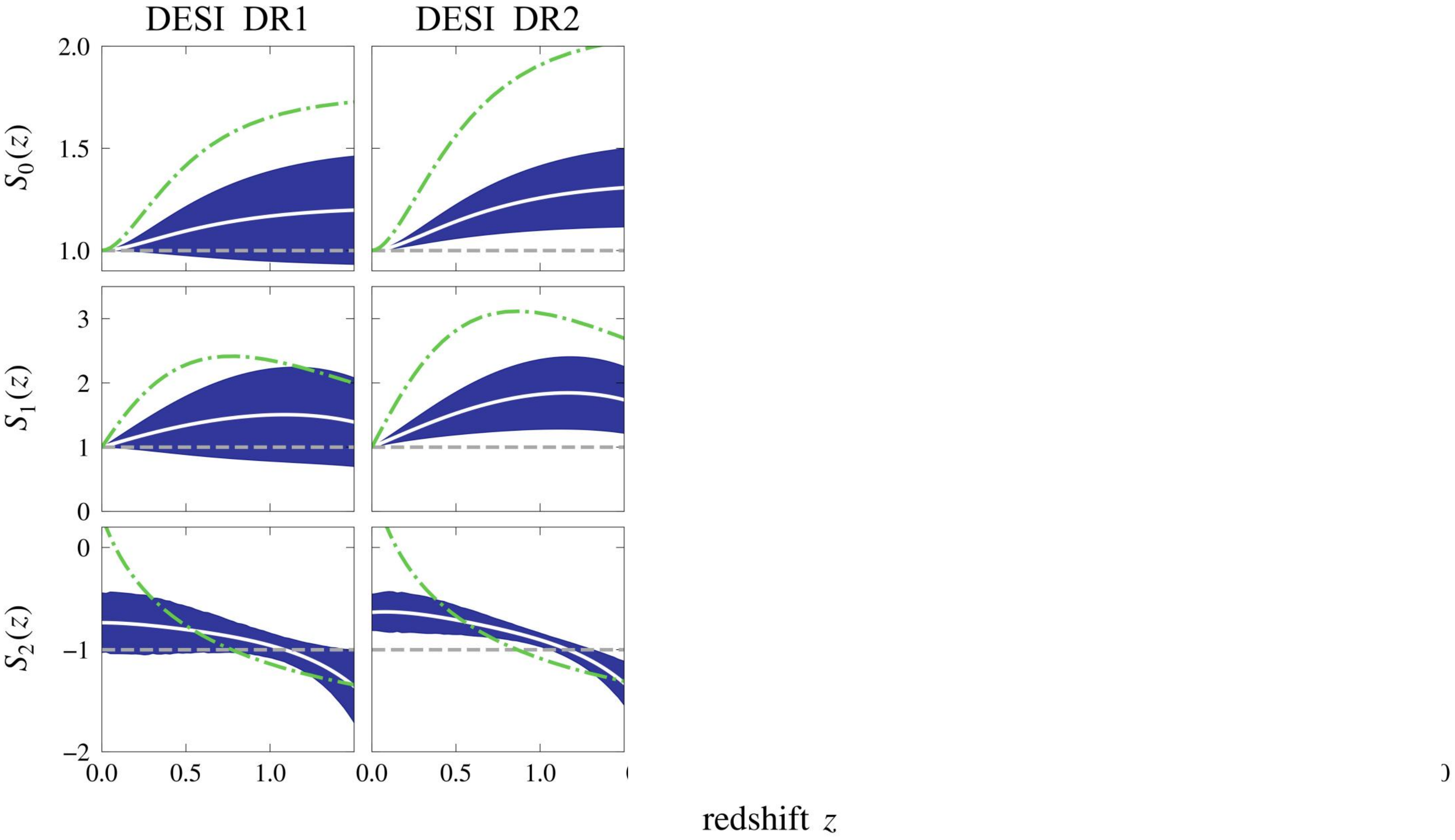
$$S_0(a) \equiv a^3 - \frac{3\,[S(a)-S(1)]}{S'(1)} = a^3 + \frac{X(a)a^3-1}{w(1)} \xrightarrow{\Lambda} 1$$

$$S_1(a) \equiv \frac{1}{a^3}\frac{S'(a)}{S'(1)} = \frac{P_{\rm DE}(a)}{P_{\rm DE}(1)} \xrightarrow{\Lambda} 1,$$

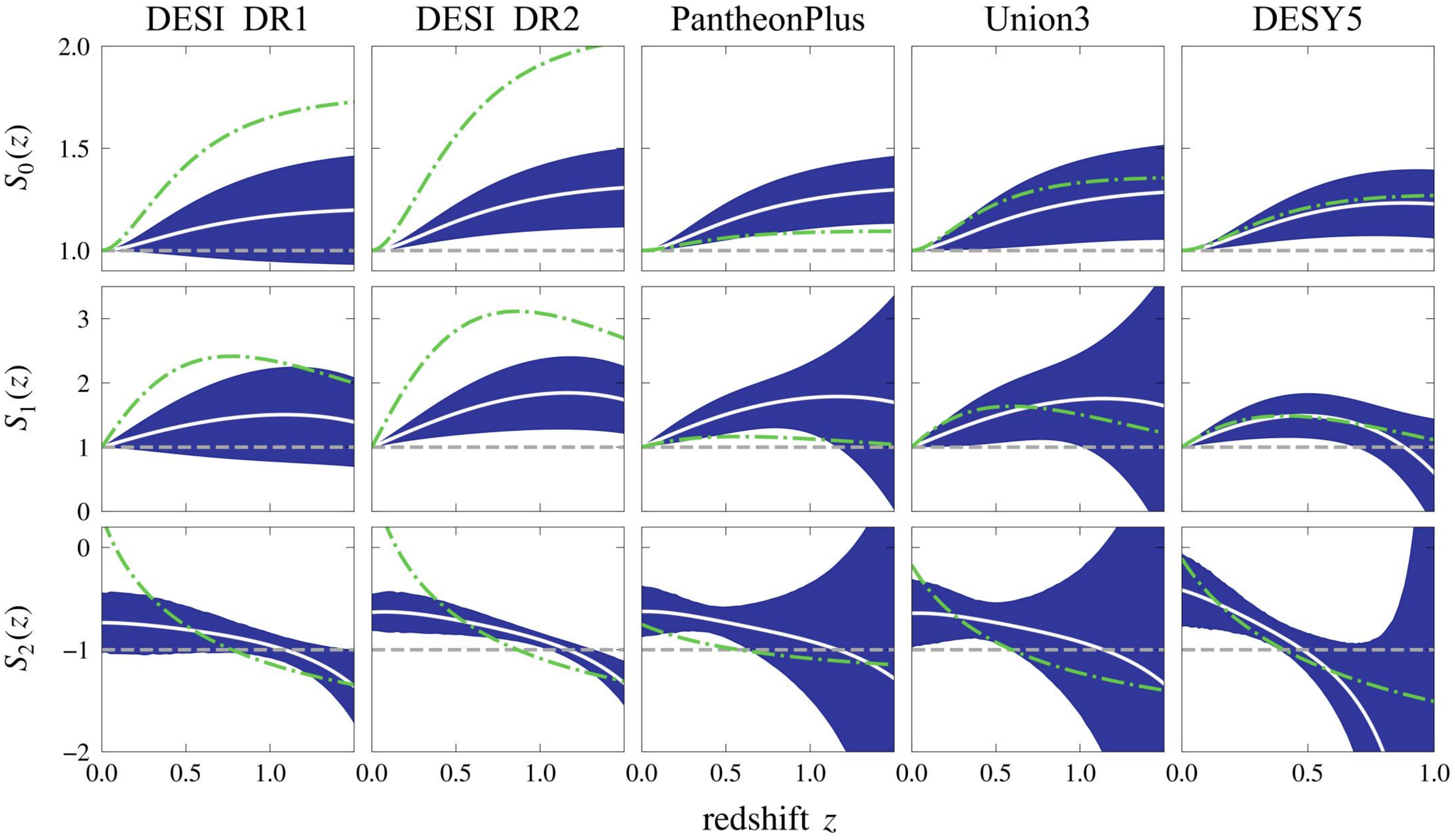
$$S_2(a) \equiv -\frac{S''(a)}{3S'(a)} = w(a) - \frac{w'(a)}{3w(a)} \xrightarrow{\Lambda} -1,$$

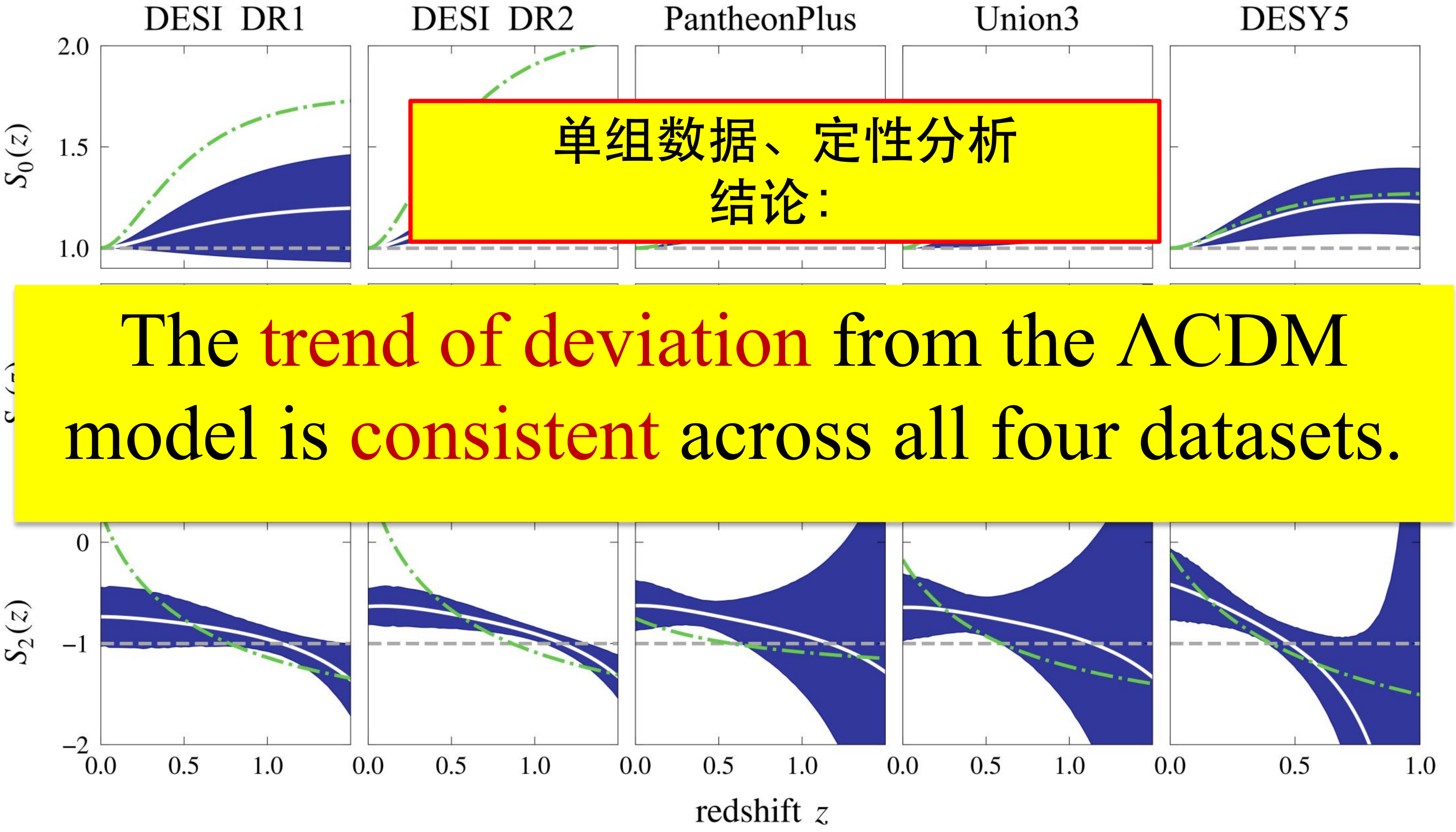


redshift z



DESI DR1
DESI DR2
$S_0(z)$
$S_1(z)$
$S_2(z)$
redshift z


DESI DR1
DESI DR2
PantheonPlus
Union3
DESY5
$S_0(z)$
$S_1(z)$
$S_2(z)$
2.0
1.5
1.0
3
2
1
0
0
−1
−2
0.0
0.5
1.0
redshift z



单组数据、定性分析结论：

The trend of deviation from the ΛCDM model is consistent across all four datasets.

Two ways to study dynamics of dark energy

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单组数据、定性分析

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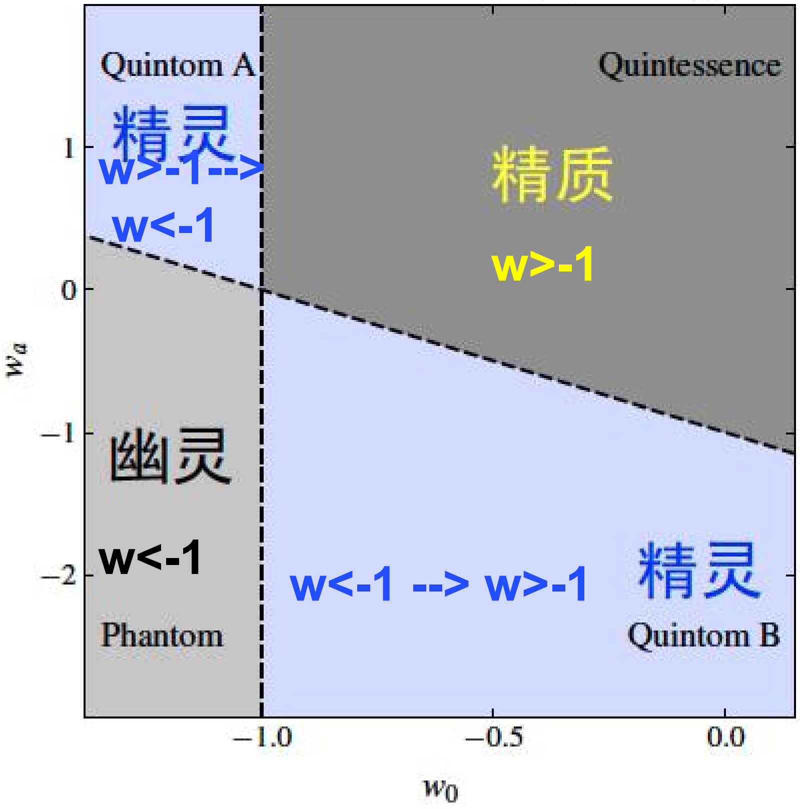
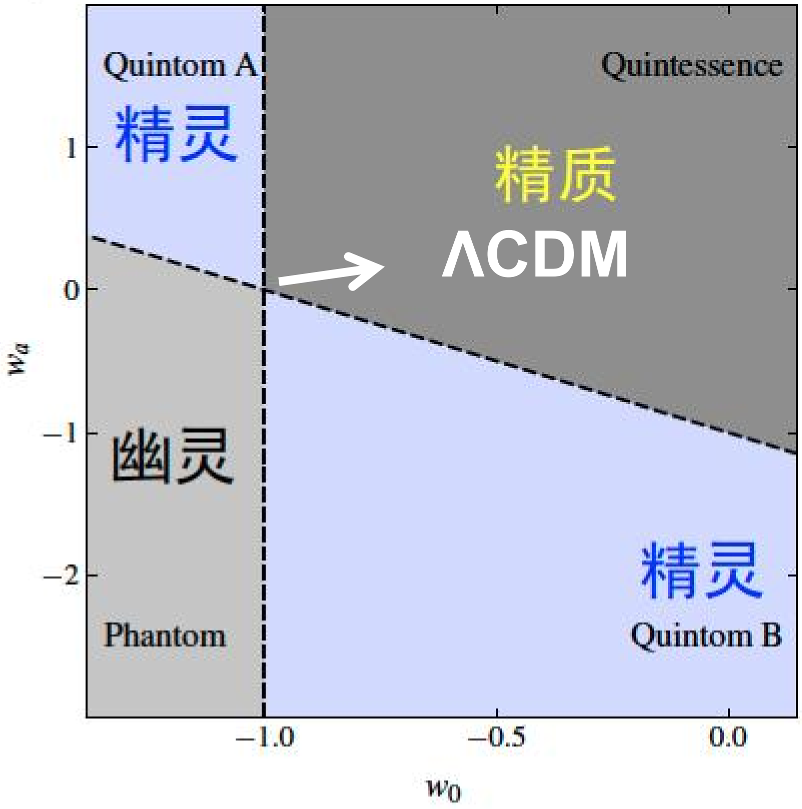
联合数据、定量分析

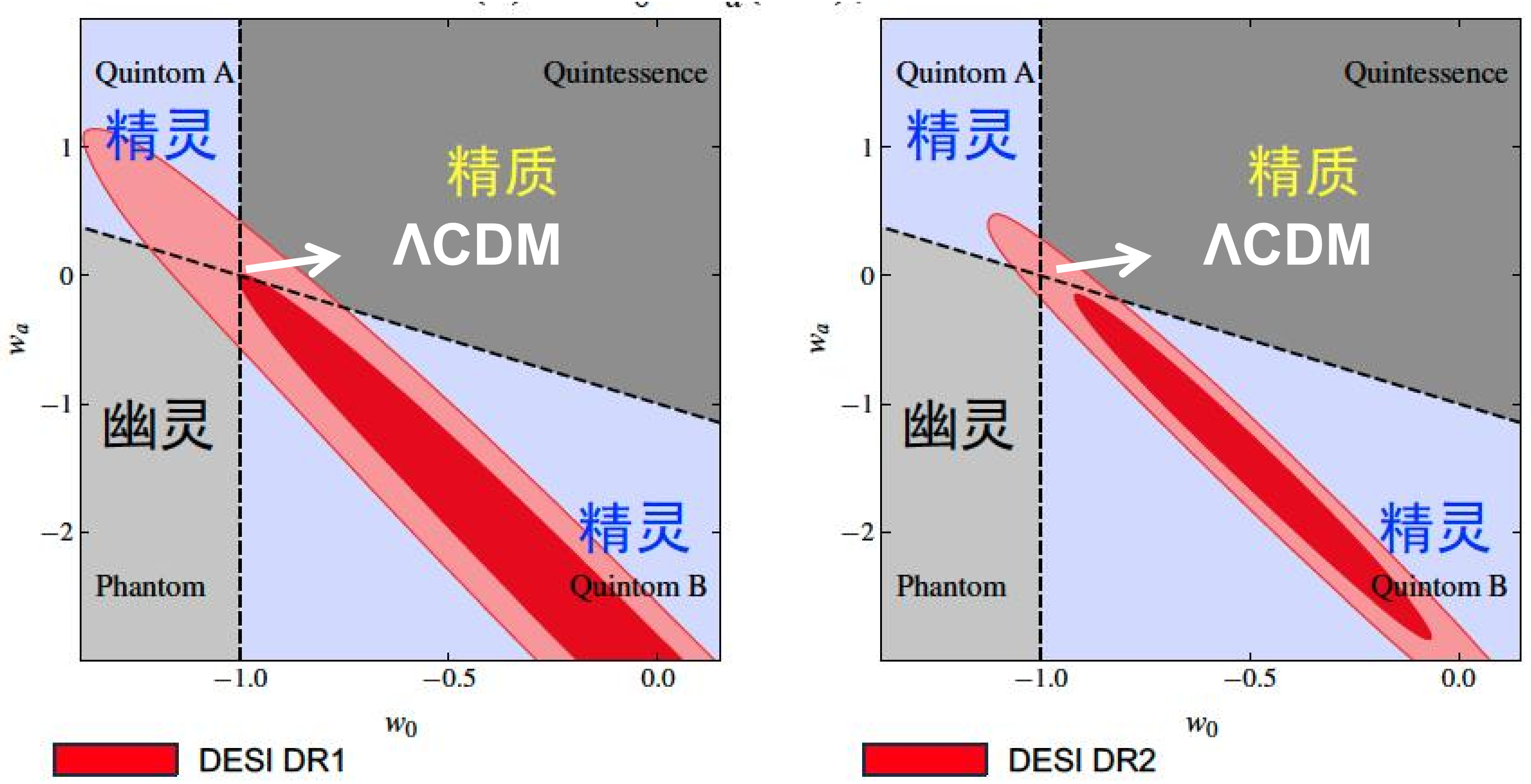
Gan Gu, Xiaoma Wang, 王钰婷, Gongbo Zhao, +DESI 合作组，arXiv：2504.06118

Varying EoS : $w(a) = w_0 + w_a(1-a)$

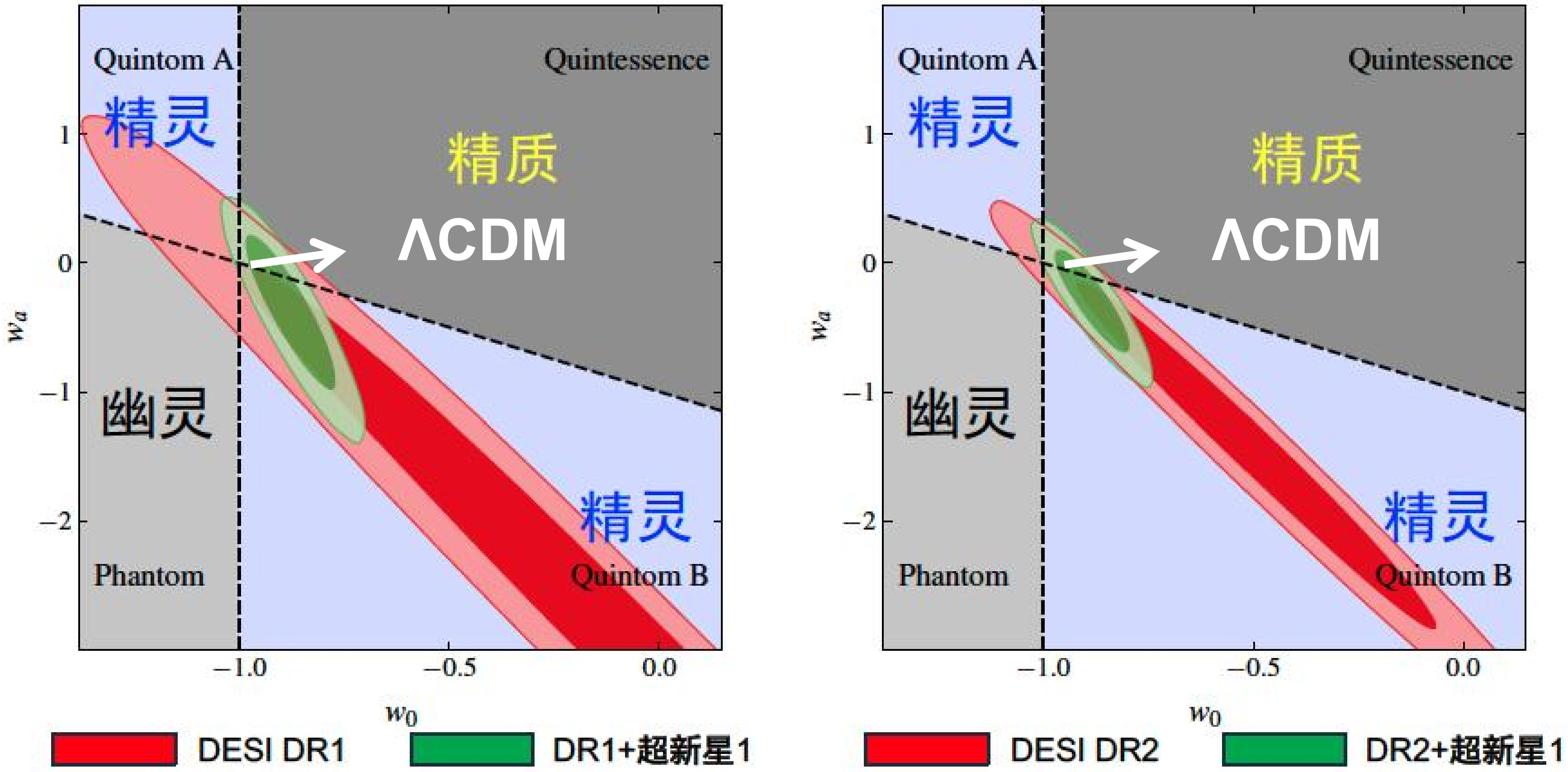




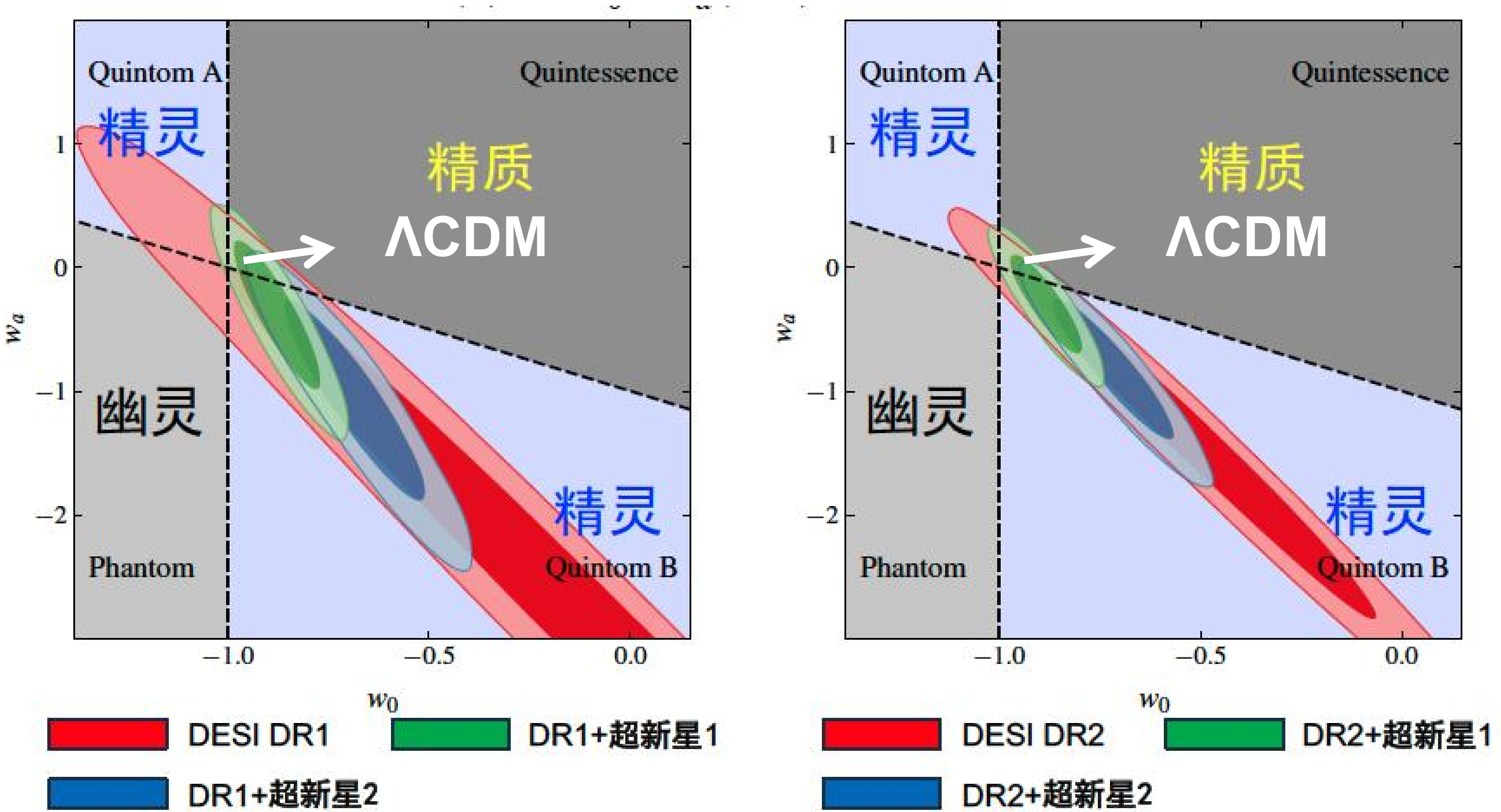
Varying EoS : $w(a) = w_0 + w_a(1-a)$



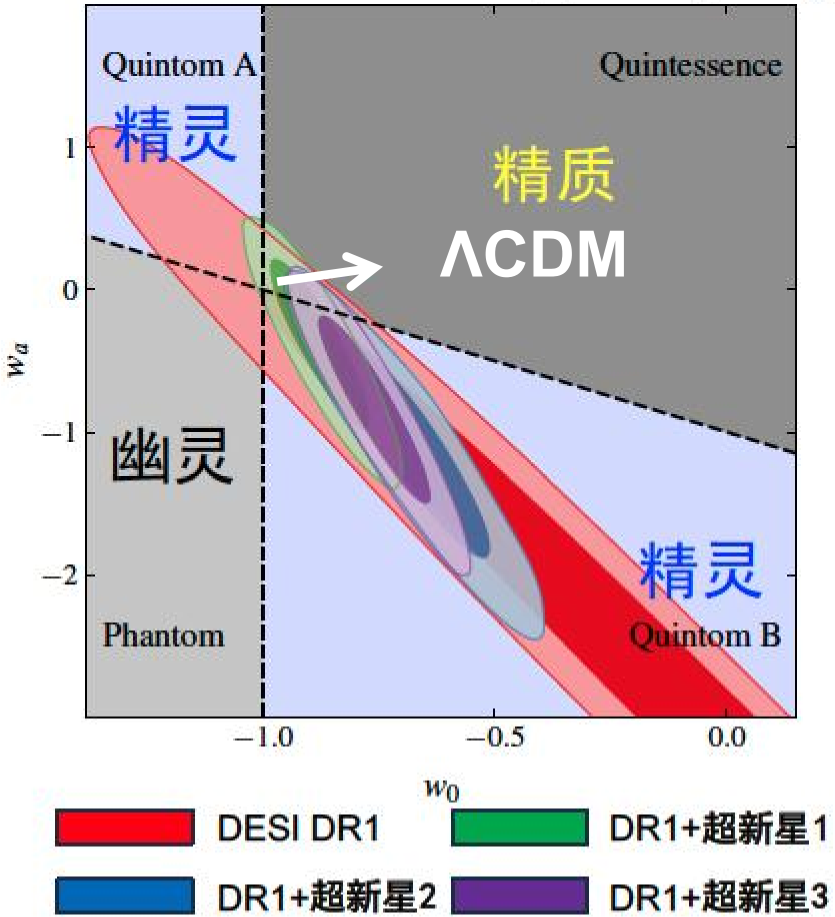
Varying EoS : $w(a) = w_0 + w_a(1-a)$

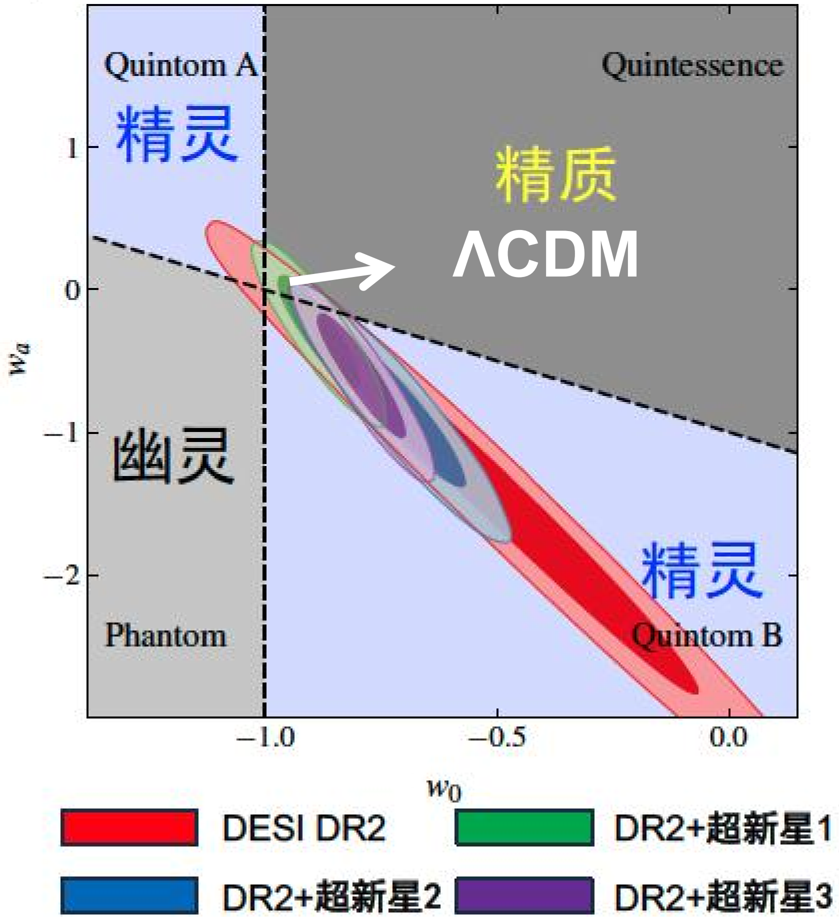


Varying EoS： $w(a) = w_0+w_a(1-a)$

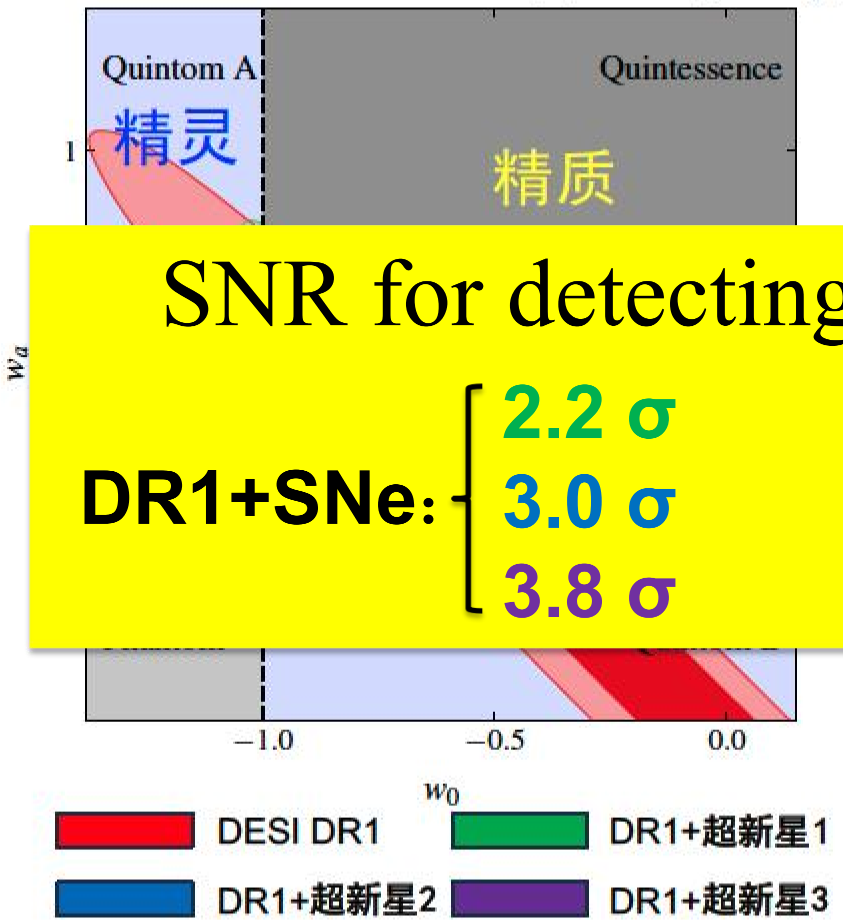


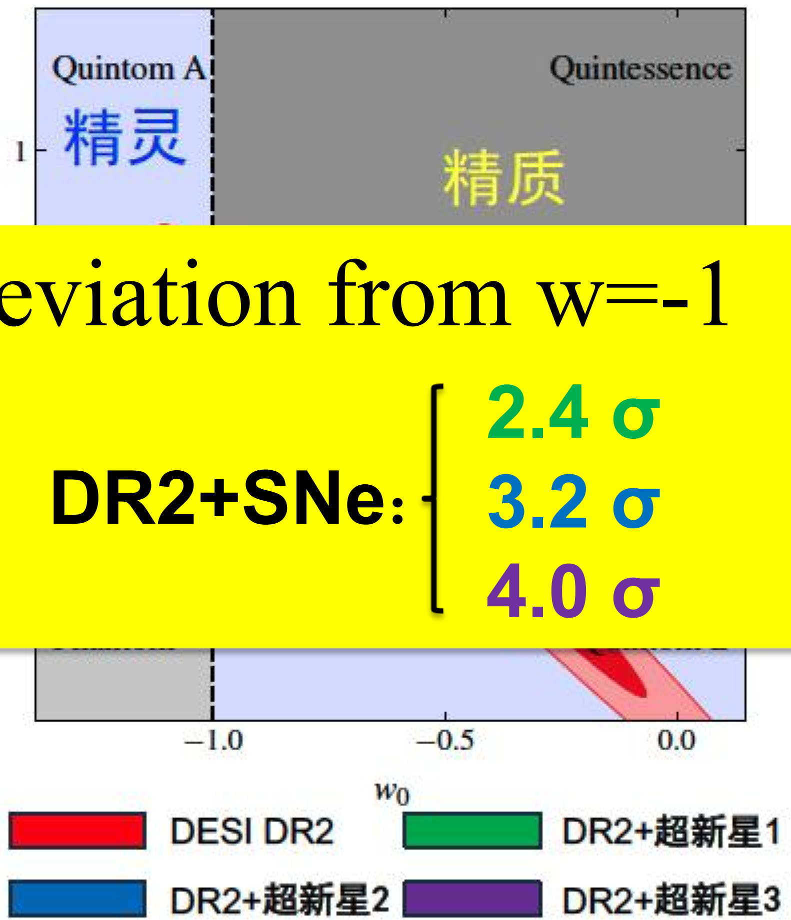
Varying EoS： $w(a) = w_0+w_a(1-a)$





Varying EoS : $w(a) = w_0 + w_a(1-a)$





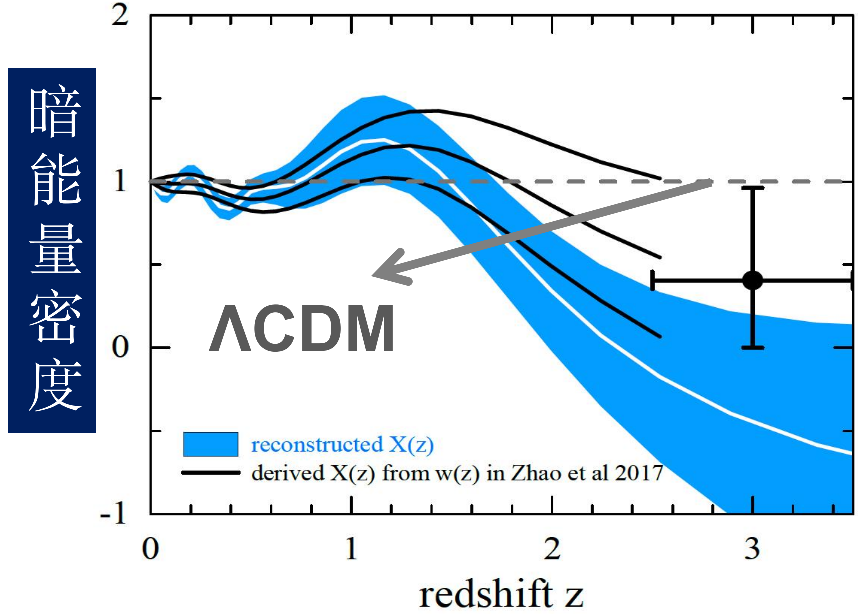
SNR for detecting deviation from w=-1

DR1+SNe: $\begin{cases} 2.2\,\sigma \\ 3.0\,\sigma \\ 3.8\,\sigma \end{cases}$

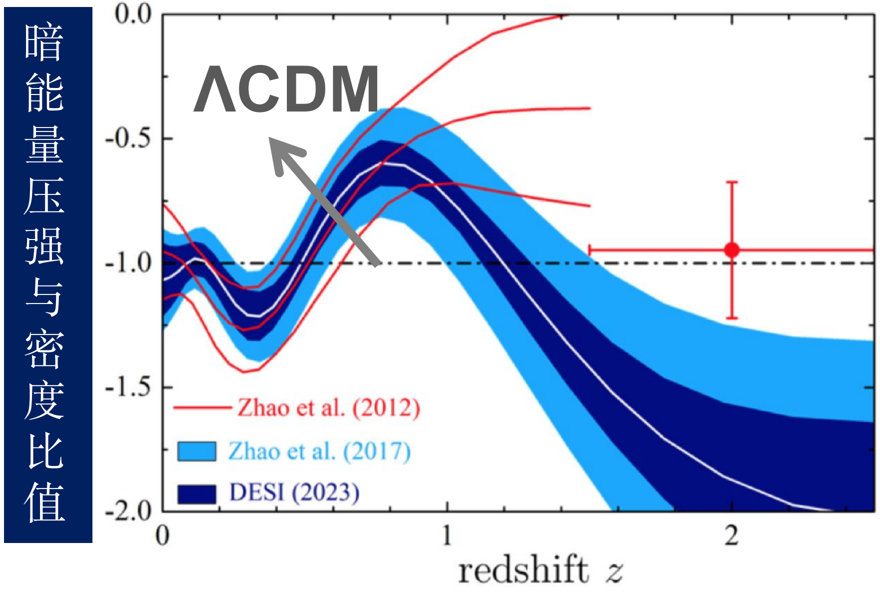
DR2+SNe: $\begin{cases} 2.4\,\sigma \\ 3.2\,\sigma \\ 4.0\,\sigma \end{cases}$

Go beyond the phenomenological ansatz

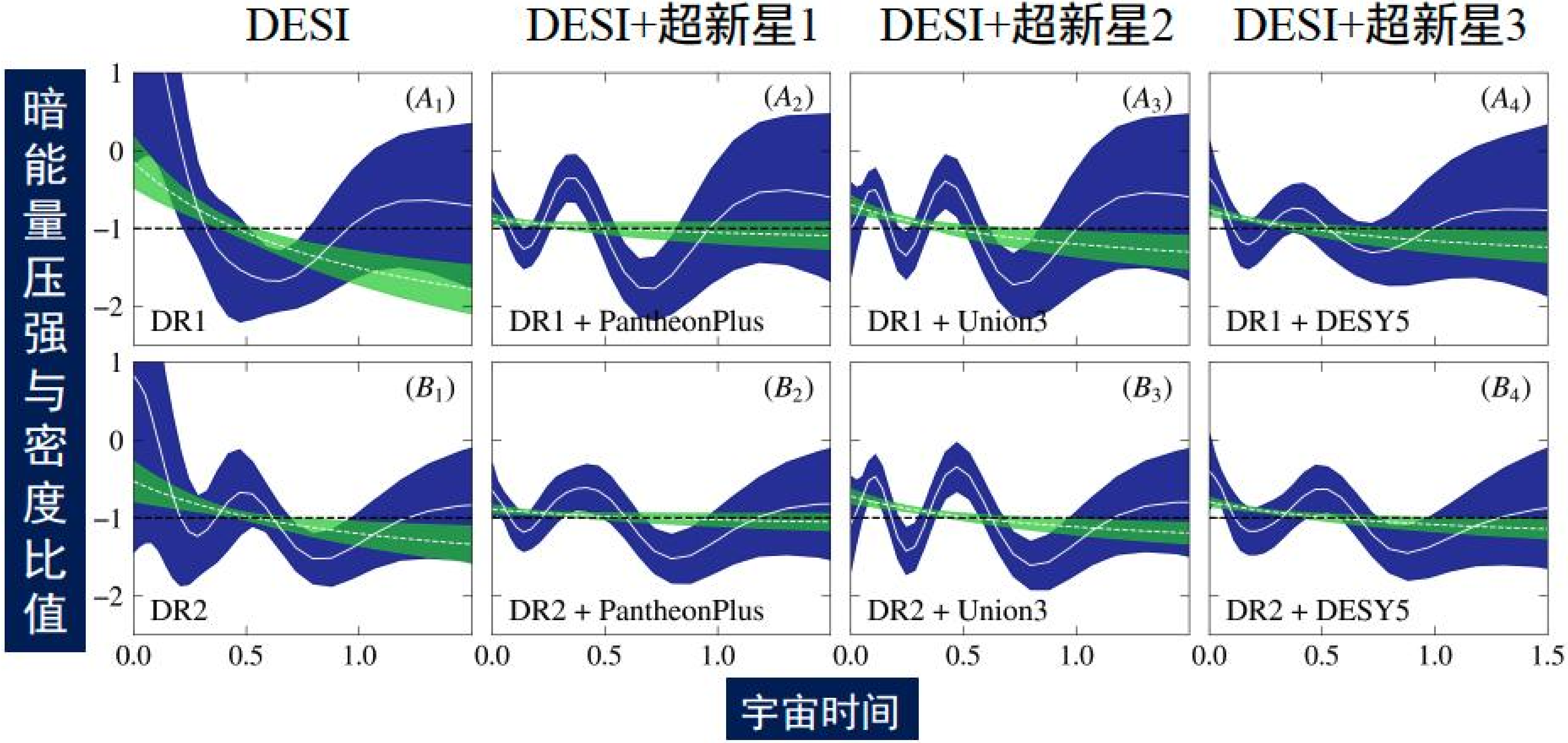
3.5 σ 动力学暗能量观测支持

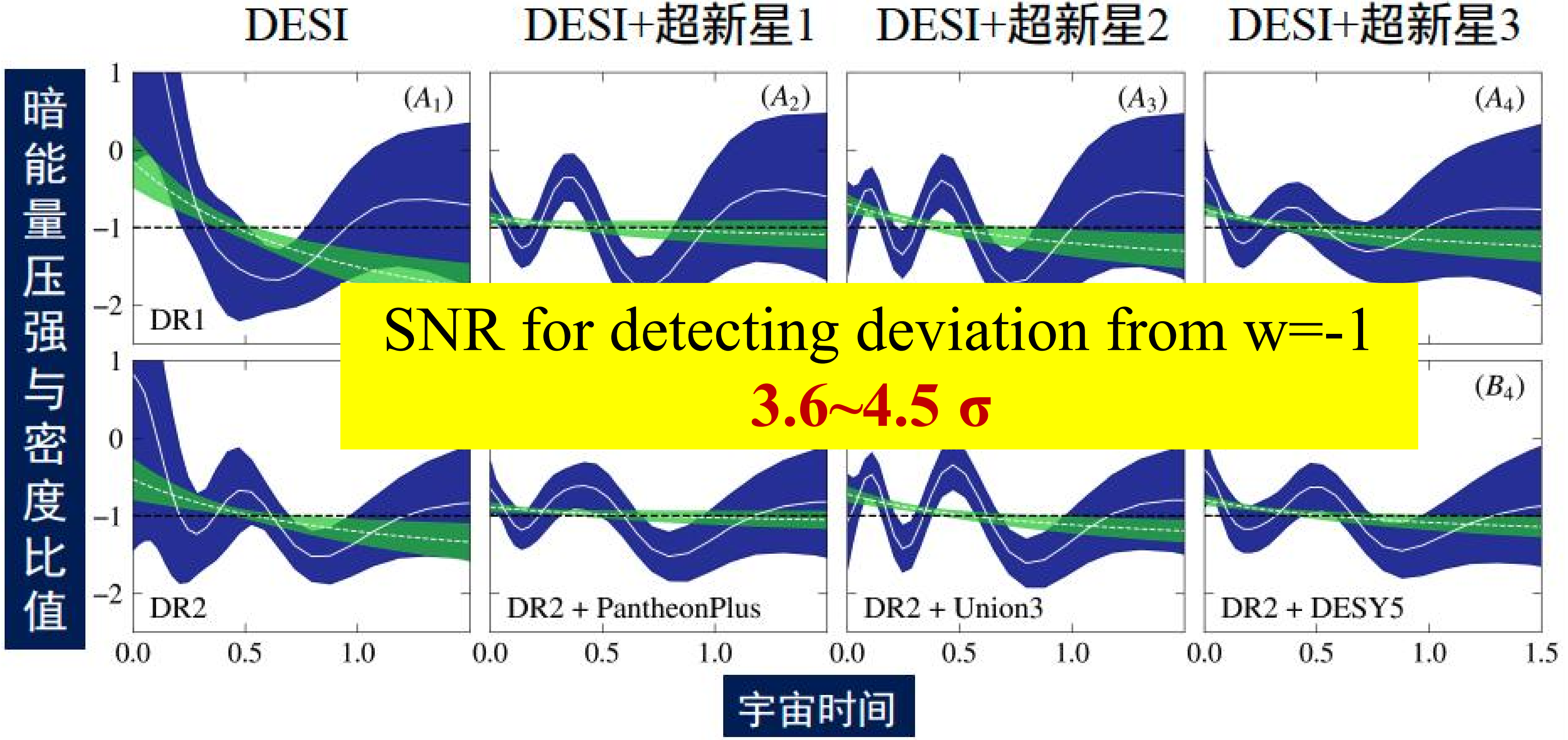


王钰婷+，2018



赵公博+，2017

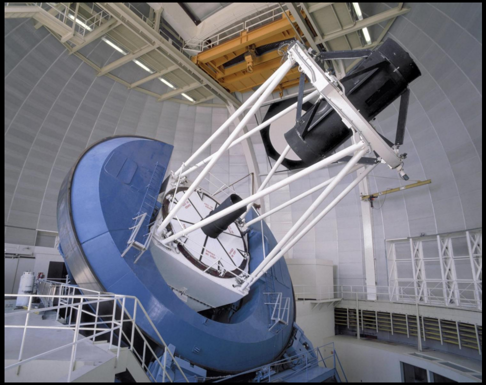

DESI
DESI+超新星1
DESI+超新星2
DESI+超新星3
暗能量压强与密度比值
(A1)
(A2)
(A3)
(A4)
(B1)
(B2)
(B3)
(B4)
DR1
DR1 + PantheonPlus
DR1 + Union3
DR1 + DESY5
DR2
DR2 + PantheonPlus
DR2 + Union3
DR2 + DESY5
1
0
−1
−2
0.0
0.5
1.0
1.5
宇宙时间

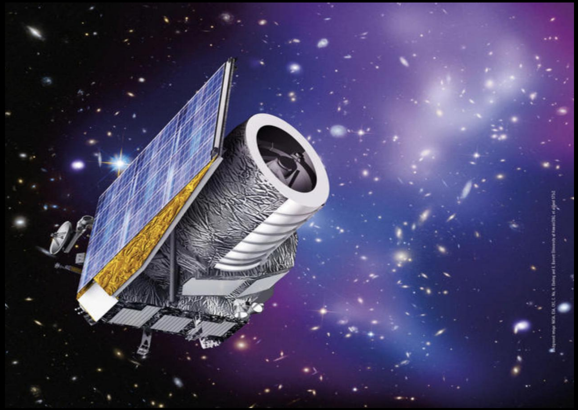


SNR for detecting deviation from w=-1

3.6~4.5 σ

Golden age of galaxy surveys

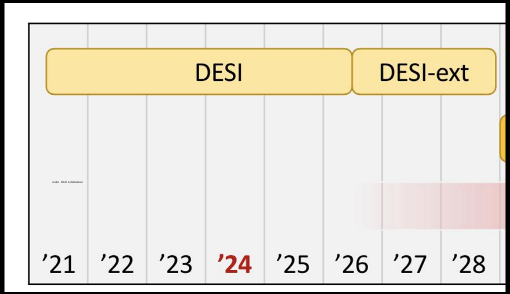




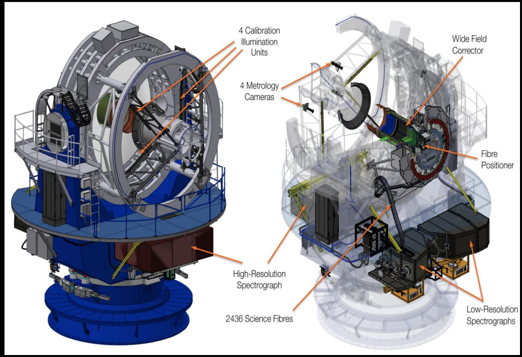
DESI, 4m (2021–2026)

- EDR: 1% survey, July‘21
- DR1 : April‘24
- DR2 : March ‘25
- Data Collection of Y5
- 14k sqdeg. one year earlier as expected

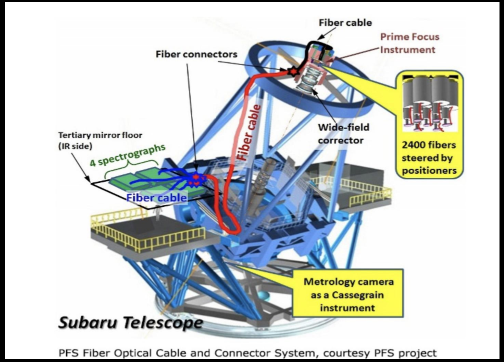
Euclid, Space mission (2023–)



Golden age of galaxy surveys

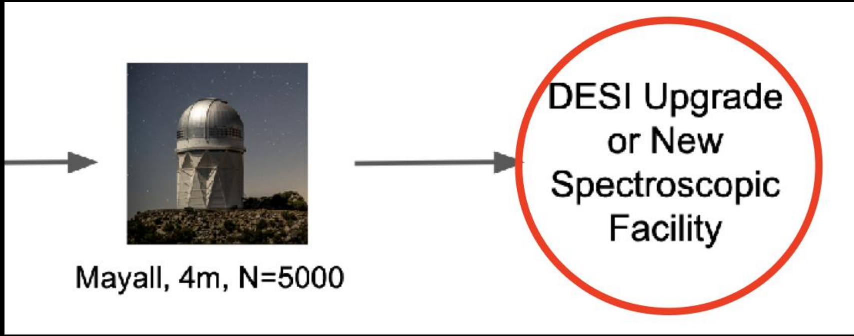


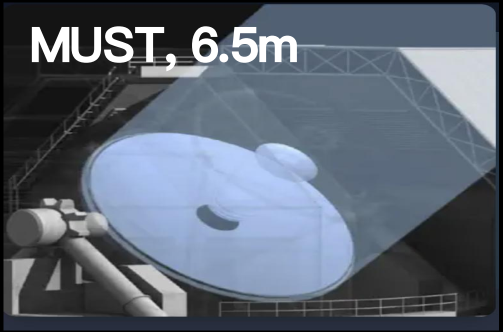
4MOST, 4m （2026-）



PFS, 8m （2025-）

CSST, space mission (2027-)





总结

- DESI 和超新星数据都显示出暗能量演化的相似趋势
- DESI Y1和Y3数据对暗能量动力学描绘出一致的图像
- 继续利用未来巡天数据深入探索暗能量的演化性质