The large scale structure of the universe

Part 1:

- **Deciphering the large scale structure (LSS)**
  - **With statistics and physics**

Part 2:

- **Tracers of LSS**
  - **Broadband power spectrum, BAO, redshift distortion, weak lensing, SZ effect, etc.**

Part 3

- **Synergies of LSS tracers**
  - **Probe DM, DE, MG, neutrino, etc.**
  - **Reduce statistical errors**
  - **Control systematic errors**

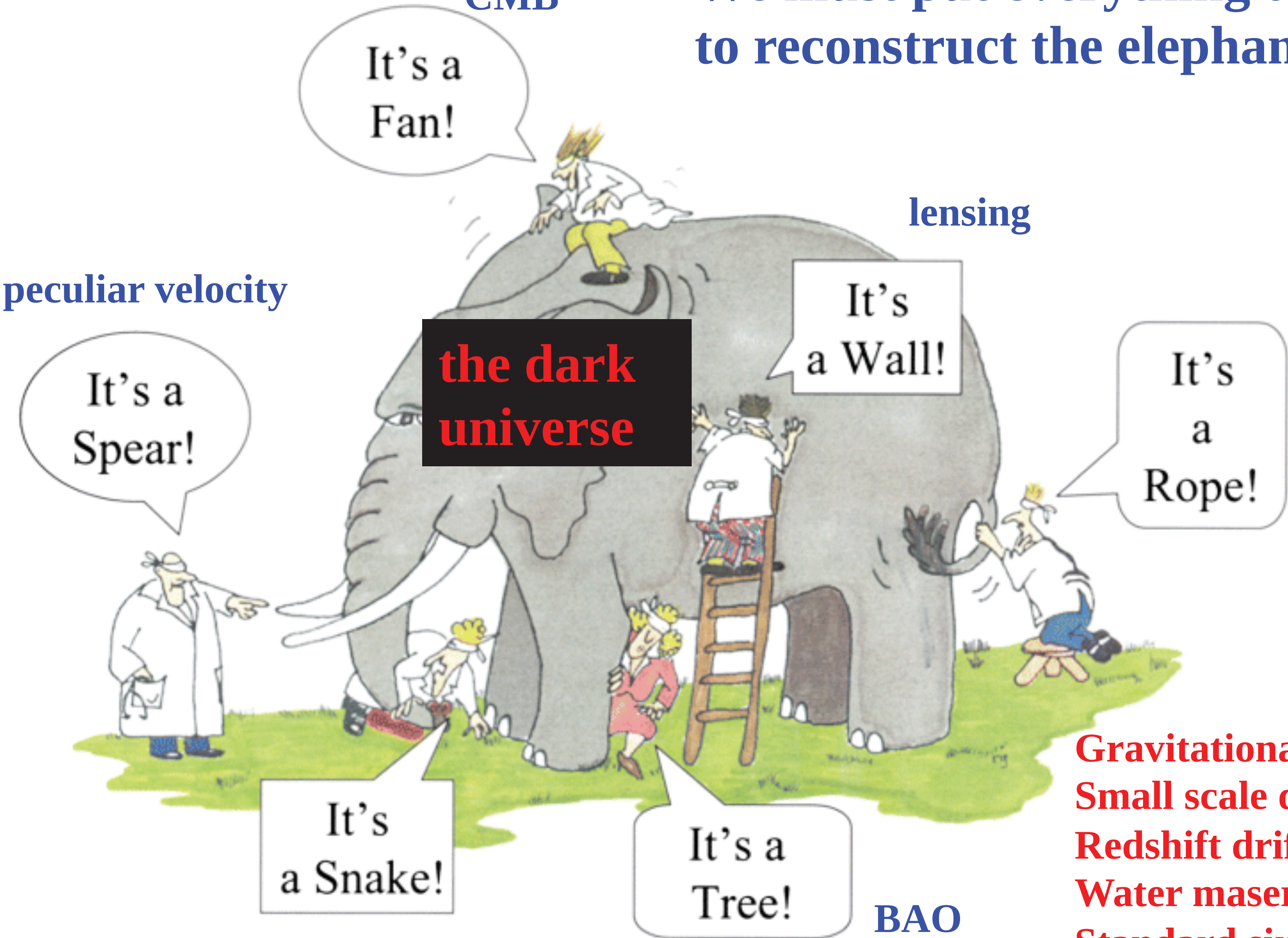
We must put everything together to reconstruct the elephant!

CMB

lensing

peculiar velocity

SNe Ia



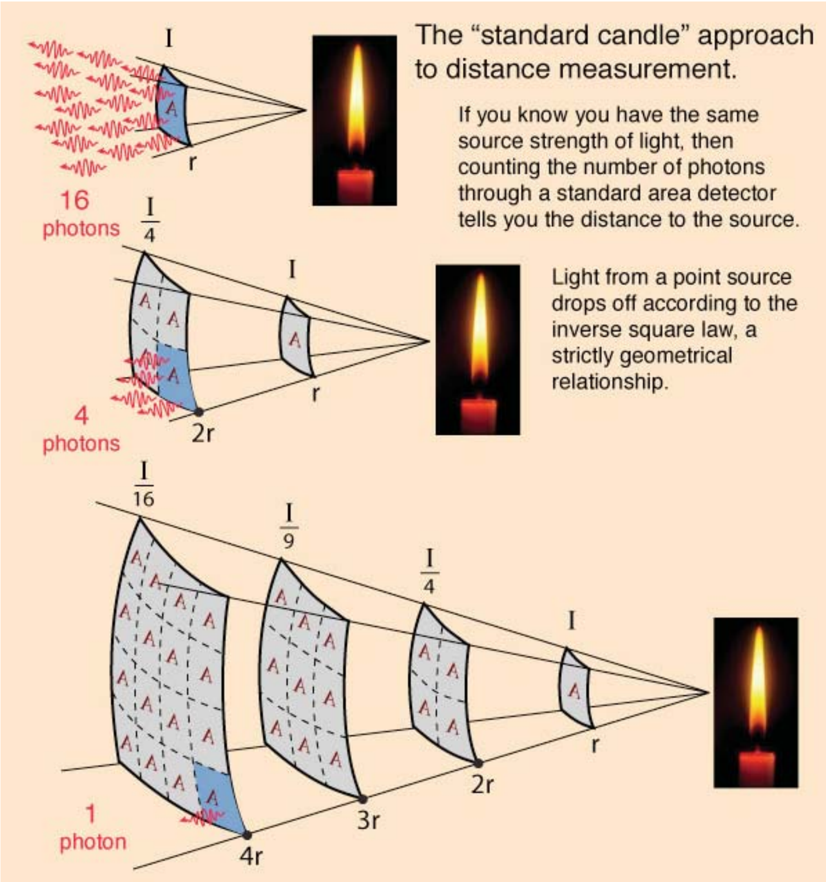
BAO

cluster abundance

Gravitational z
Small scale dynamics
Redshift drift
Water maser
Standard sirens
Relativistic effects in observables
…….

1+1>2

Smoking gun of the dark energy was first detected in the year 1998, through unexpected dimming of type Ia supervovae



超新星标准烛光-》宇宙学距离-》宇宙膨胀速度-》宇宙膨胀加速度

$$\ddot{a}_{\mathrm{today}} > 0$$

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

宇宙中存在压强为负的未知能量场！被称为暗能量

$$\frac{P}{\rho} < -\frac{1}{3}$$

Riess et al. 1998
Perlmutter et al. 1999

Riess et al. 2005

宇宙加速膨胀(暗能量）的发现

- 1998年，Perlmutter et al., Riess, Schmidt et al. 等通过超新星观测发现宇宙加速膨胀
- “表明基本粒子和引力理论或不正确、或不完备、、、需要基础物理革命来全面理解加速膨胀”--暗能量特别工作组报告（2006）

2011年
诺贝尔物理奖

Photo: Lawrence Berkeley National Lab

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Scanpix/AFP

Adam G. Riess

The Nobel Prize in Physics 2011 was awarded *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"* with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.

宇宙学常数的复活和动力学暗能量的诞生

THE ASTROPHYSICAL JOURNAL, **284**:439–444, 1984 September 15

1984年，Jim Peebles预言了宇宙学常数的复活

TESTS OF COSMOLOGICAL MODELS CONSTRAINED BY INFLATION

P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University
Received 1984 February 6; accepted 1984 March 23

ABSTRACT

The inflationary scenario requires that the universe have negligible curvature along constant-density surfaces. In the Friedmann-Lemaître cosmology that leaves us with two free parameters, Hubble's constant H_0 and the density parameter Ω_0 (or, equivalently, the cosmological constant Λ). I discuss here tests of this set of models from local and high-redshift observations. The data agree reasonably well with $\Omega_0 \sim 0.2$.

Subject heading: cosmology

THE ASTROPHYSICAL JOURNAL, **325**:L17–L20, 1988 February 15

1988年，Peelbes和Ratra提出了动力学暗能量。后来被称为quintessence

COSMOLOGY WITH A TIME-VARIABLE COSMOLOGICAL "CONSTANT"

P. J. E. PEEBLES AND BHARAT RATRA
Joseph Henry Laboratories, Princeton University
Received 1987 October 20; accepted 1987 November 23

ABSTRACT

If the potential $V(\phi)$ of the scalar field that drove inflation had a power-law tail at large ϕ, $V \approx \phi^{-\alpha}$, the mass density, ρ_ϕ, associated with ϕ would act like a cosmological constant that decreases with time less rapidly than the mass densities of matter and radiation. If ρ_ϕ were appreciable at the present epoch it could help reconcile the low dynamical estimates of the mean mass density with the negligibly small space curvature preferred by inflation.

Subject headings: cosmology — early universe

Evidence for dark energy from the cosmic microwave background alone using the Atacama Cosmology Telescope lensing measurements

2011

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For the first time, verified the cosmic acceleration with CMB data alone

(Primary CMB+CMB lensing)

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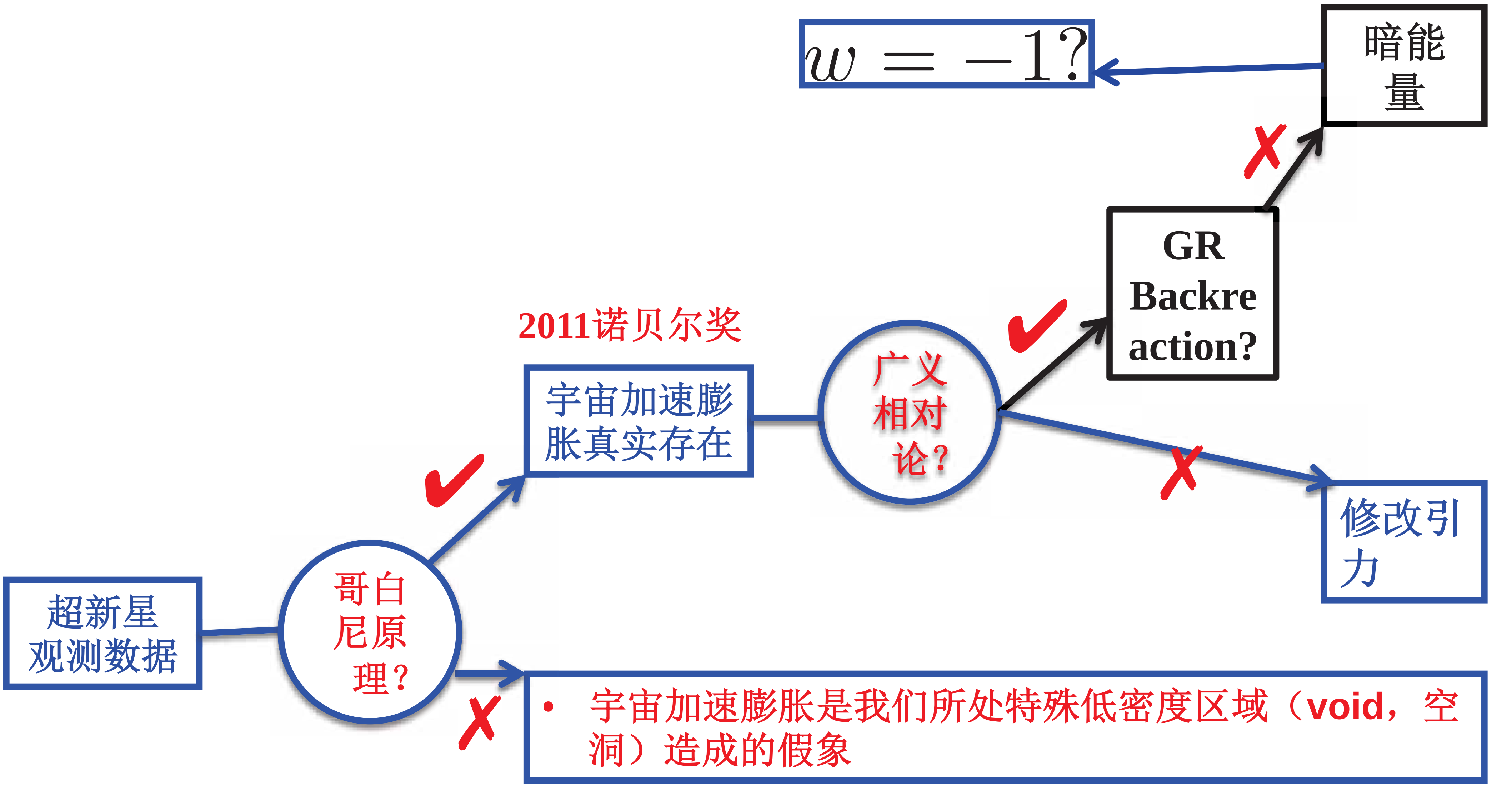
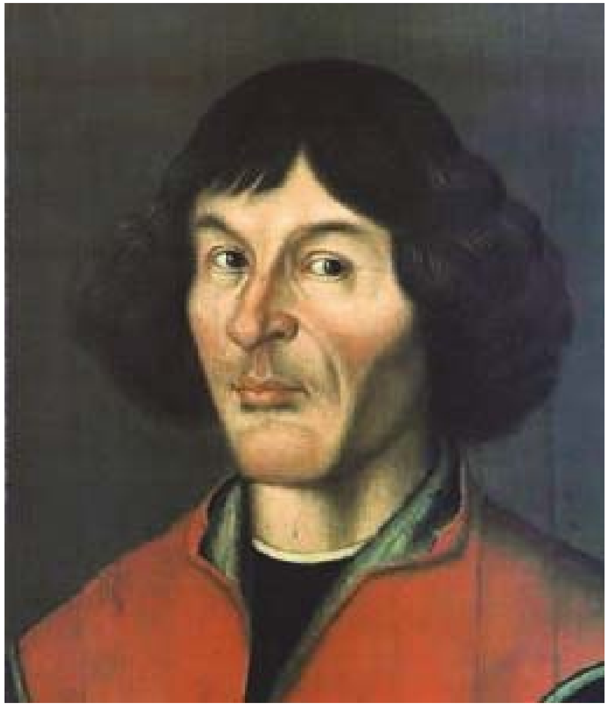
For the first time, measurements of the cosmic microwave background radiation (CMB) alone favor cosmologies with $w = -1$ dark energy over models without dark energy at a 3.2-sigma level. We demonstrate this by combining the CMB lensing deflection power spectrum from the Atacama Cosmology Telescope with temperature and polarization power spectra from the Wilkinson Microwave Anisotropy Probe. The lensing data break the geometric degeneracy of different cosmological models with similar CMB temperature power spectra. Our CMB-only measurement of the dark energy density Ω_Λ confirms other measurements from supernovae, galaxy clusters and baryon acoustic oscillations, and demonstrates the power of CMB lensing as a new cosmological tool.

Possibilities of “cosmic acceleration”



The Copernican Principle



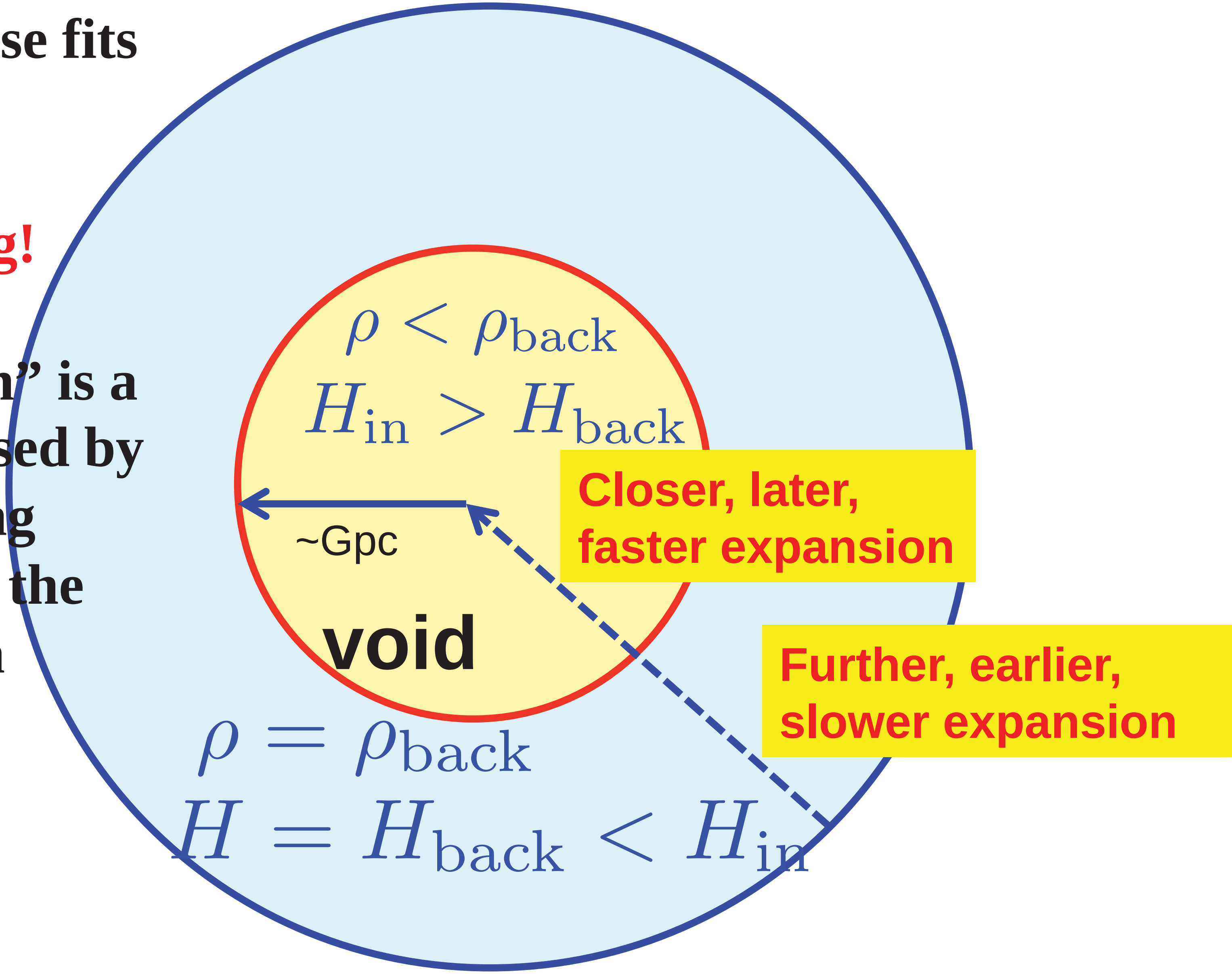
1473-1543

大致相当于数学中的
边界条件或者物理中
的初始条件

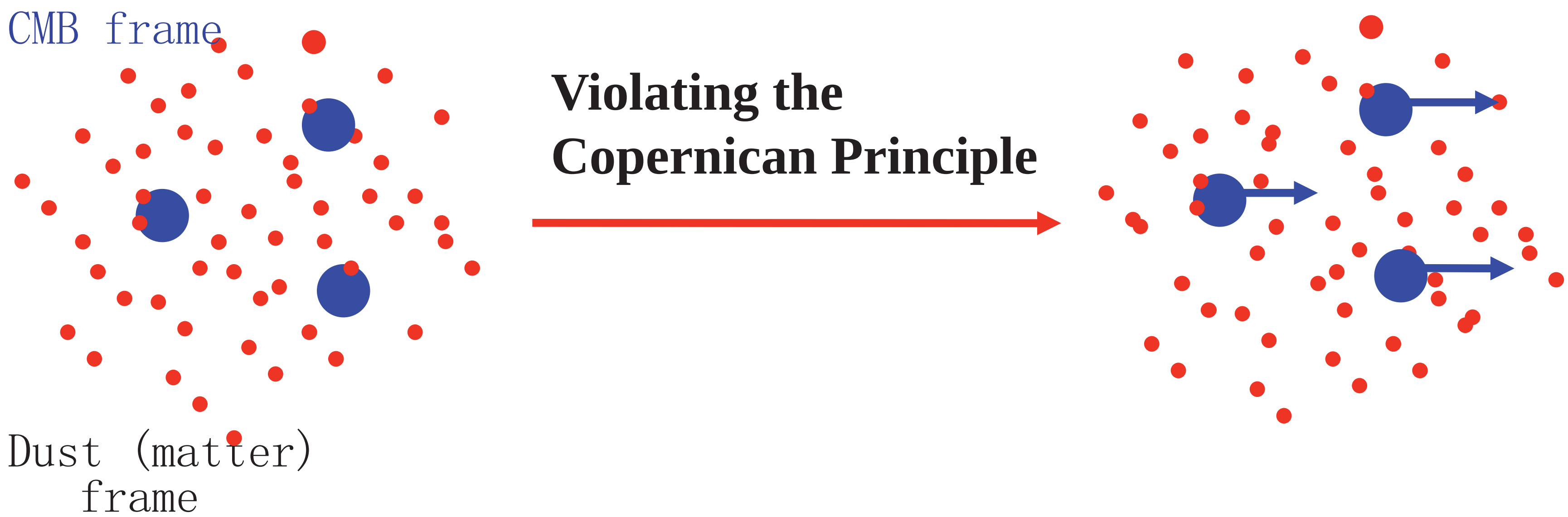
- It claims that the universe has no center
  - We do not live in a special region
  - The universe observed by us is a unbiased sample of THE UNIVERSE
- Cornerstone of cosmology
  - Leads to the Cosmological Principle
  - Prerequisite to explore universal laws through cosmological observations
  - Deep connection to cosmic origin/vacuum
- If violated, can
  - cosmic deceleration–>acceleration
  - Lambda-> dynamical DE
  - …

Void model: sacrifice CP to explain "cosmic acceleration"

- This universe fits SN data.
- But it is decelerating!
- "Cosmic acceleration" is a mirage caused by void—strong violation of the Copernican Principle.



The solution: a Gpc scale bulk motion



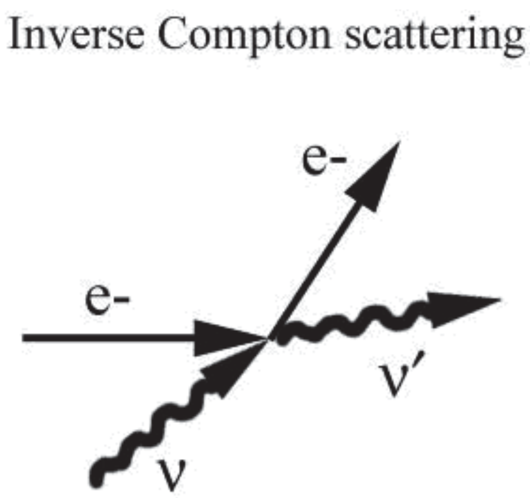
- In a homogeneous universe, no relative bulk motion between the two frames.

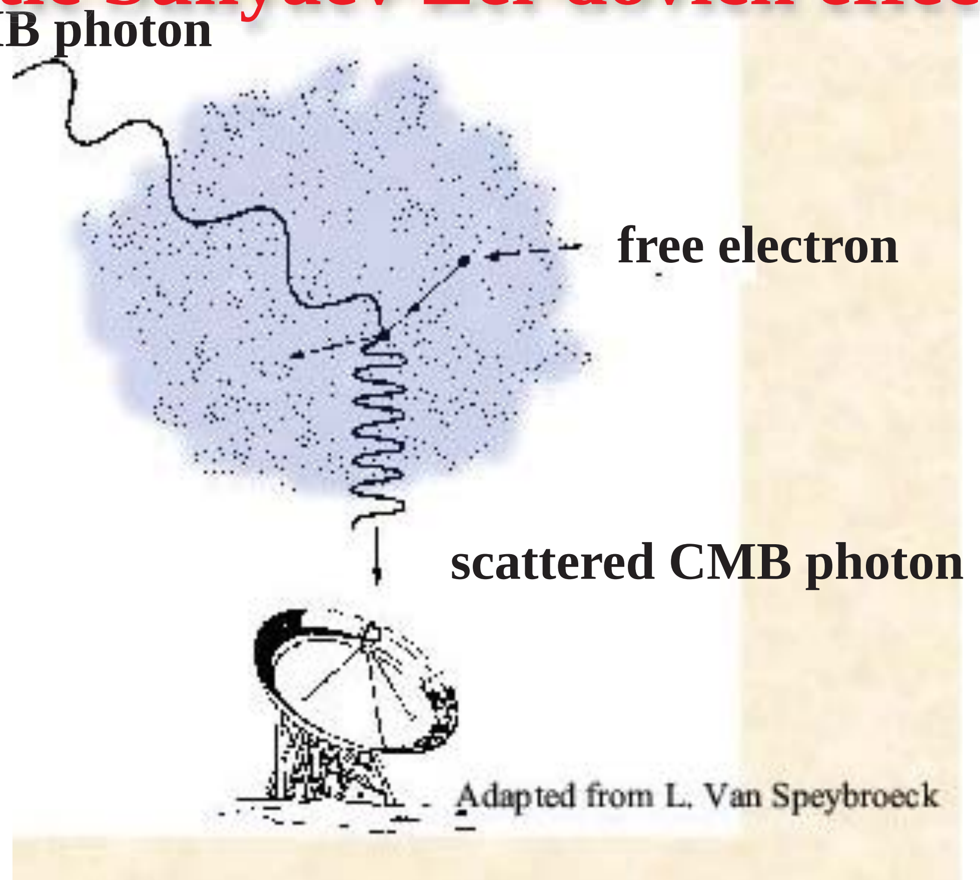
➢ Violating the Copernican Principle inevitably causes NET relative motion between the two frames.

➢ Gpc scale bulk motion

Goodman 1995. A very brilliant paper, but not many people know

This motion causes the kinetic Sunyaev Zel'dovich effect





Moving free electrons scatter off CMB photons through ICS, causes fluctuations in CMB temperature (the kinetic SZ effect).

$$\frac{\Delta T}{T}\Big|_{\mathrm{kSZ}}(\hat{n}) = \int \sigma_T n_e(\hat{n}, z) \frac{\mathbf{v}(\hat{n}, z) \cdot \hat{n}}{c} a d\chi$$

Zel'dovich & Sunyaev, 1980

Can be a significant effect

$$\frac{\Delta T}{T} \sim 2\mu K (\frac{\tau}{0.001})(\frac{v}{2000km/s})\frac{\delta}{0.1}$$

$$v \sim 2 \times 10^3 \mathrm{km}/s (\frac{H}{H_0})(\frac{\delta\rho/\rho}{0.01})(\frac{L}{\mathrm{Gpc}/h})$$

Degree/arcminute scale kSZ effect

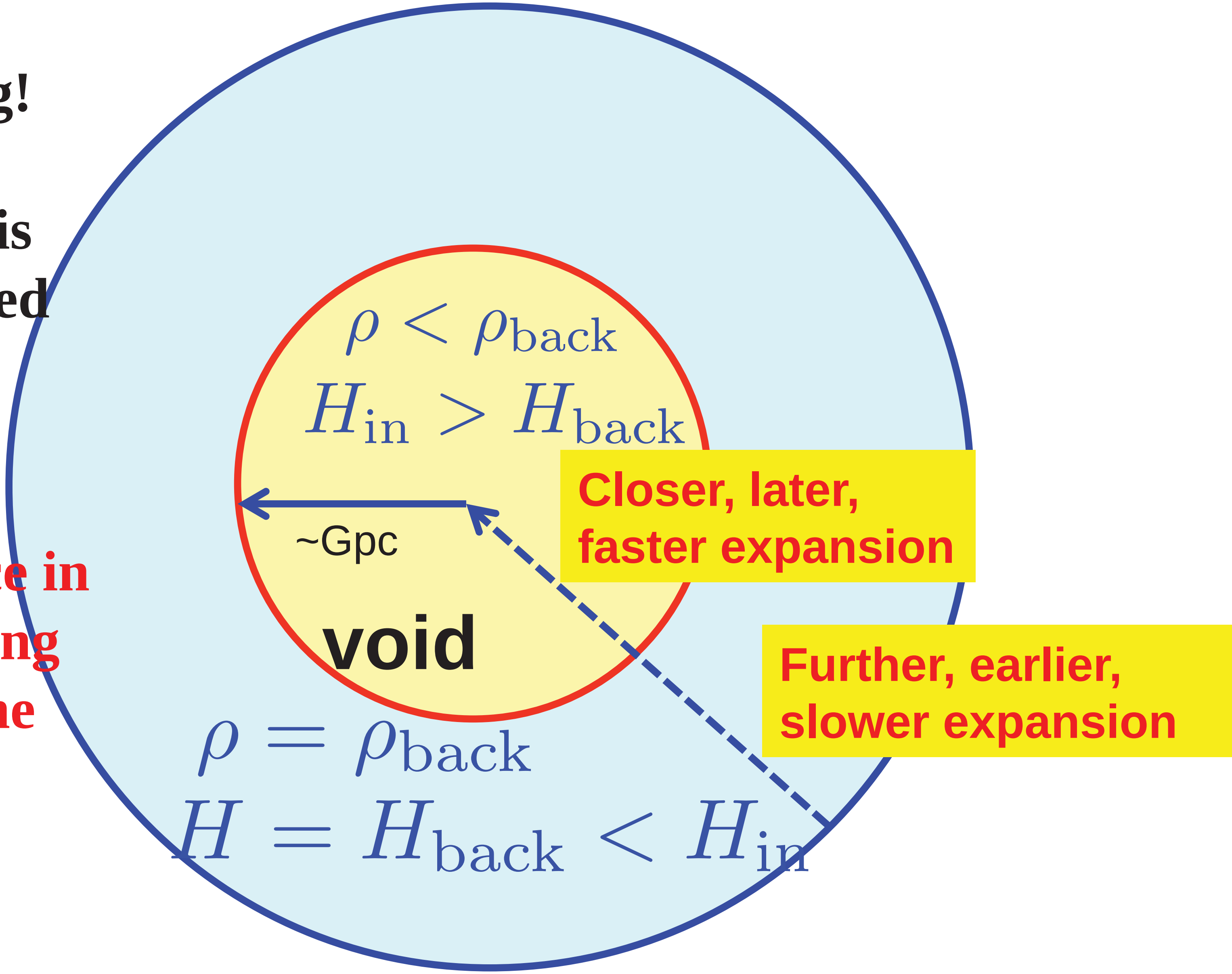
Bulk flow from large/ horizon scale inhomogeneities

$$\frac{\Delta T}{T}|_{\mathrm{kSZ}}(\hat{n}) = \int \sigma_T n_e(\hat{n}, z) \frac{\mathbf{v}(\hat{n}, z) \cdot \hat{n}}{c} a d\chi$$

Strong inhomogeneities at small scales

Testing the void model and strong violation of Copernican principle by kSZ

The universe Is decelerating! “Cosmic acceleration” is a mirage caused by void



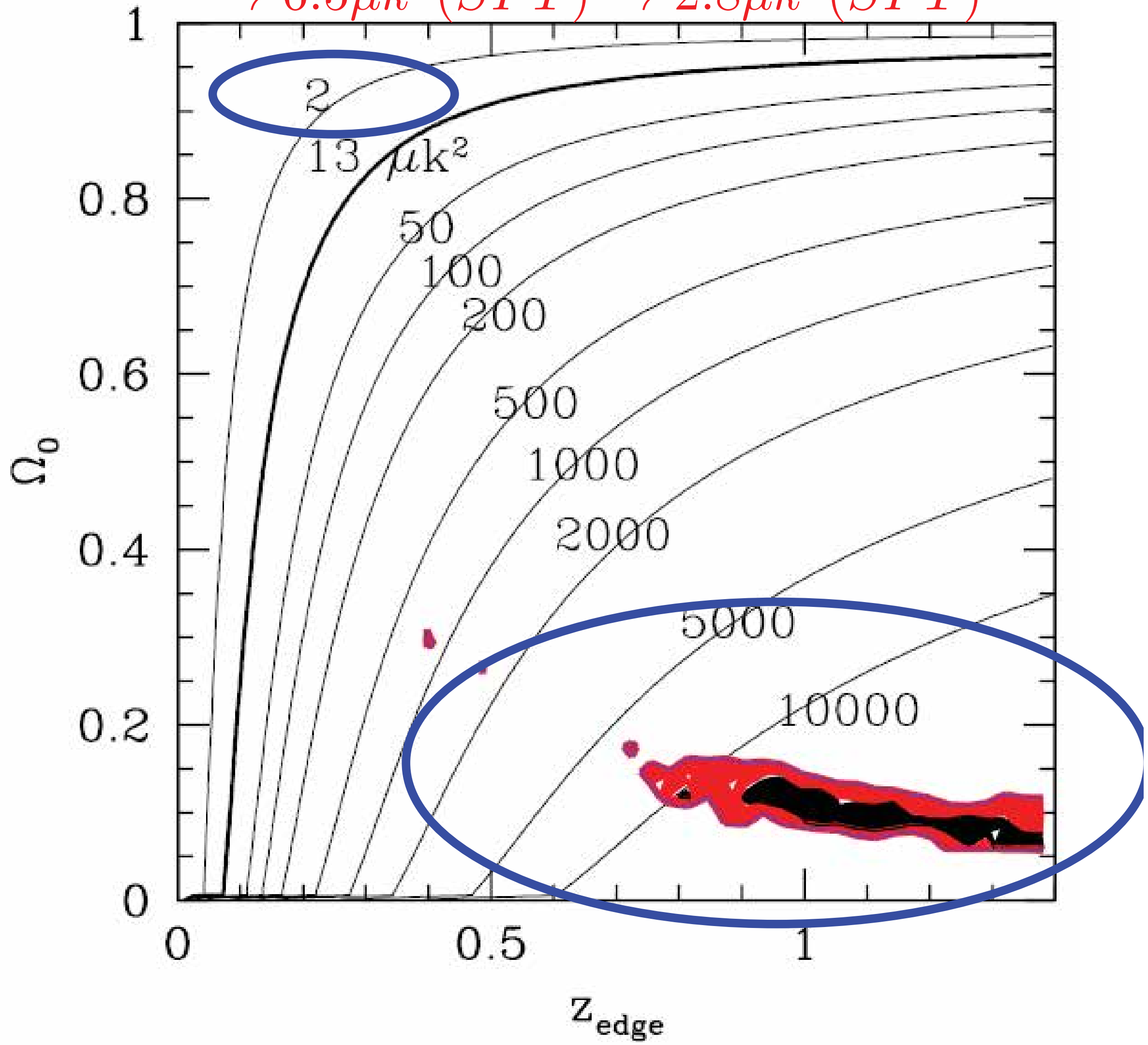
10% difference in density. A strong violation of the Copernican Principle.

Rule out the void model
Rule out strong violation of CP

$13\mu k^2(SPT) \rightarrow 8\mu k^2(ACT)$

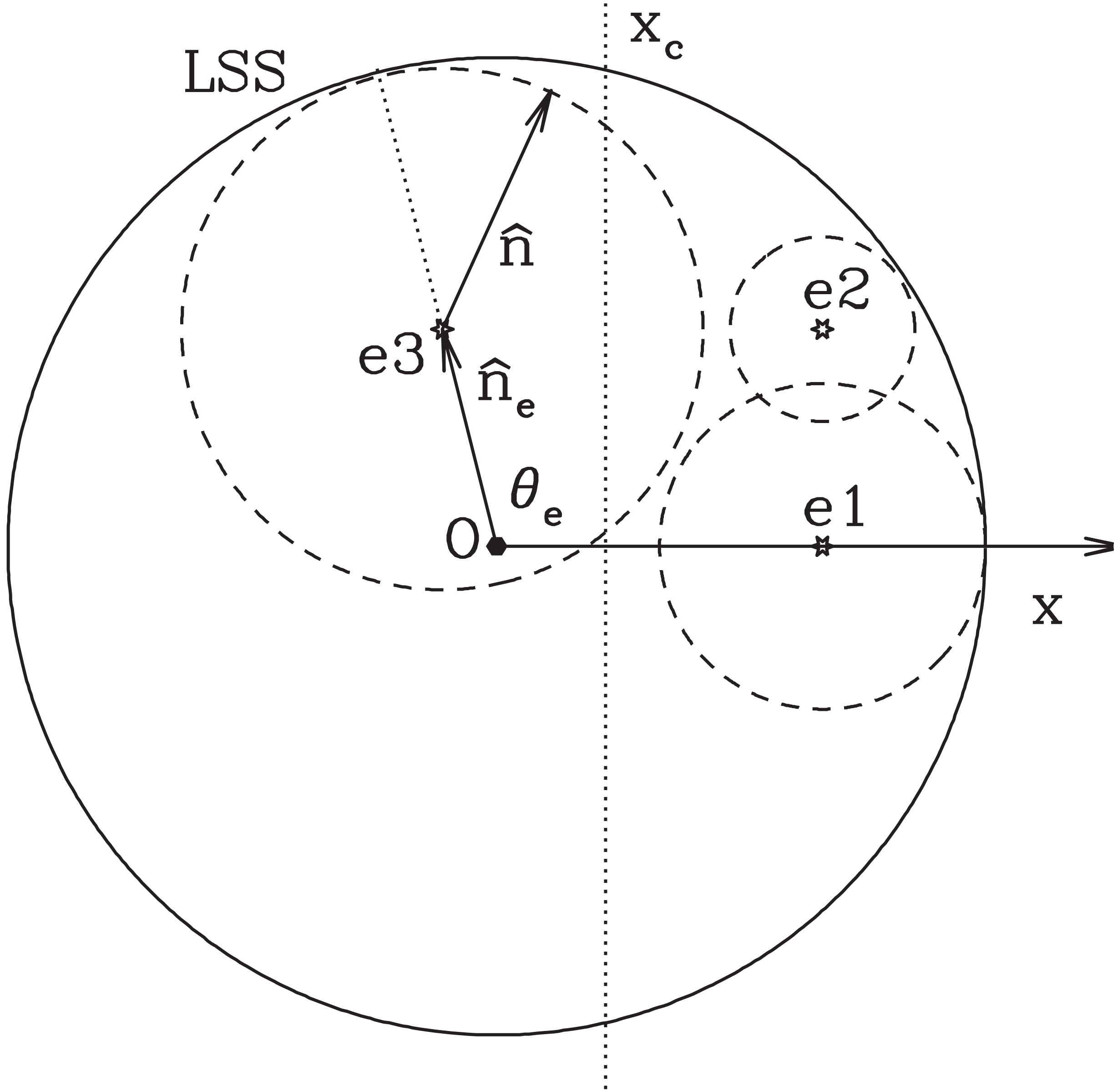
$\rightarrow 6.5\mu k^2(SPT) \rightarrow 2.8\mu k^2(SPT)$

- **Observation: upper limit on the diffuse kSZ effect (2.8-13 uk^2) by ACT/SPT**
- **Void: ~10^3-10^4 uk^2**
- **All void models explaining SNe Ia are ruled out**
- **Strong violation of the Copernican principle at 1Gpc and above radial scale is ruled out.**
- **The "Cosmic acceleration" is indeed real!**



ZPJ & Stebbins, 2011, PRL

The kSZ effect allows us to observe the whole horizon from all viewpoints

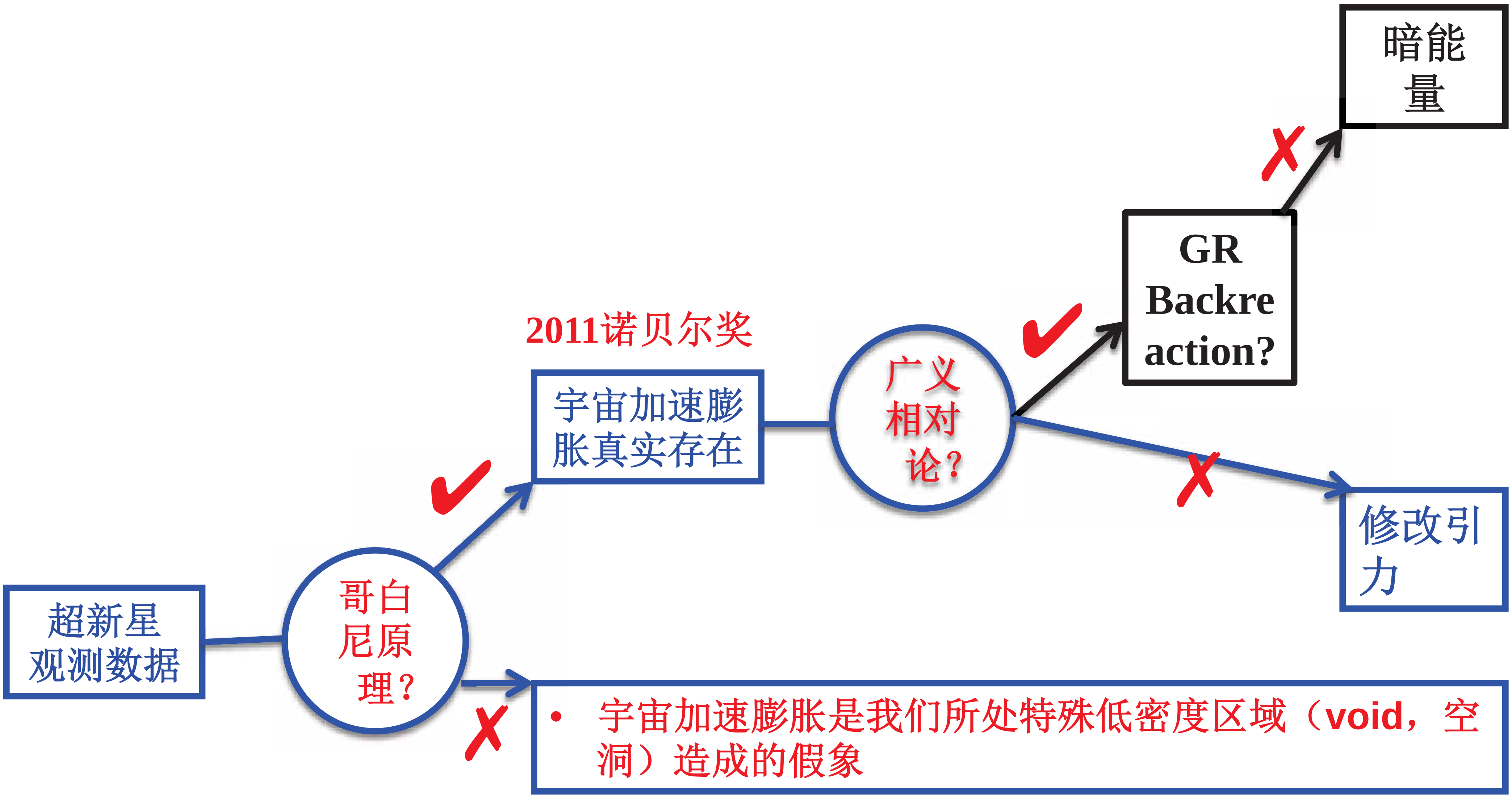


Probe horizon scale inhomogeneities by kSZ

- **Free of lightcone problem**
  - Free electrons are everywhere.
  - They observe the universe from every viewpoint.
  - They send the information to us by ICS.
- **Free of cosmic variance problem**
  - kSZ=electron number overdensity * bulk flow
  - Gpc bluk flow -> arcmin kSZ. Many independent modes.

- Probe dark flow (ZPJ 2010; Li, ZPJ & Chen 2012; Li+, 2017)
- Test void model and the Copernican Principle (ZPJ & Stebbins, 2011)
- Vacuum decay (Pen & ZPJ, 2014)
- Bubble collision (ZPJ & Johnson, 2015)

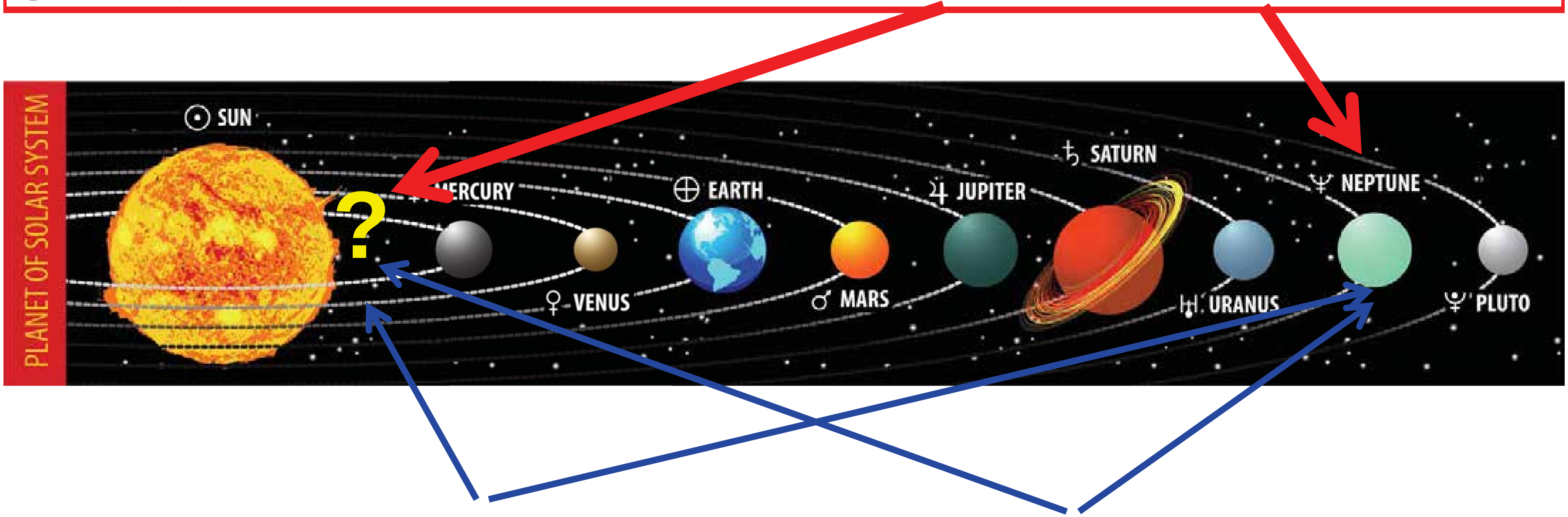
Cosmic acceleration, the Copernican Principle, dark energy, modified gravity, and beyond



Is GR valid at cosmolgical scale?

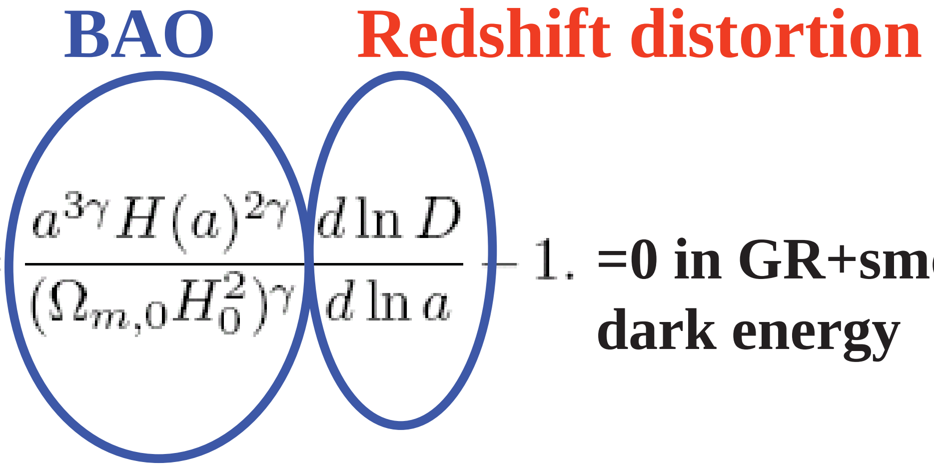
Newtonian gravity in 19th century vs. general relativity in 21st century:

Based on observations of the visible universe, Newtonian gravity predicted the existence of Vulcan and Neptune



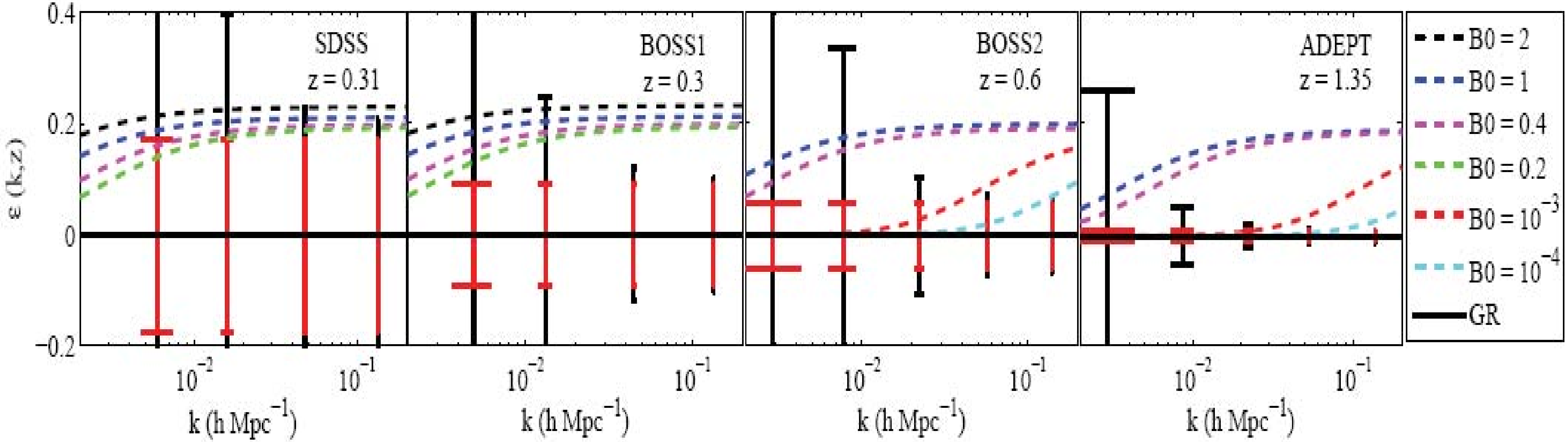
Based on observations of the visible universe, Einstein gravity predicted dark matter and dark energy

BAO+RSD to test GR consistency relation



$$\epsilon(k,a) = \Omega_m^{-\gamma(a)} \frac{d\ln D}{d\ln a} - 1 = \frac{a^{3\gamma} H(a)^{2\gamma}}{(\Omega_{m,0} H_0^2)^\gamma} \frac{d\ln D}{d\ln a} - 1.$$

=0 in GR+smooth dark energy



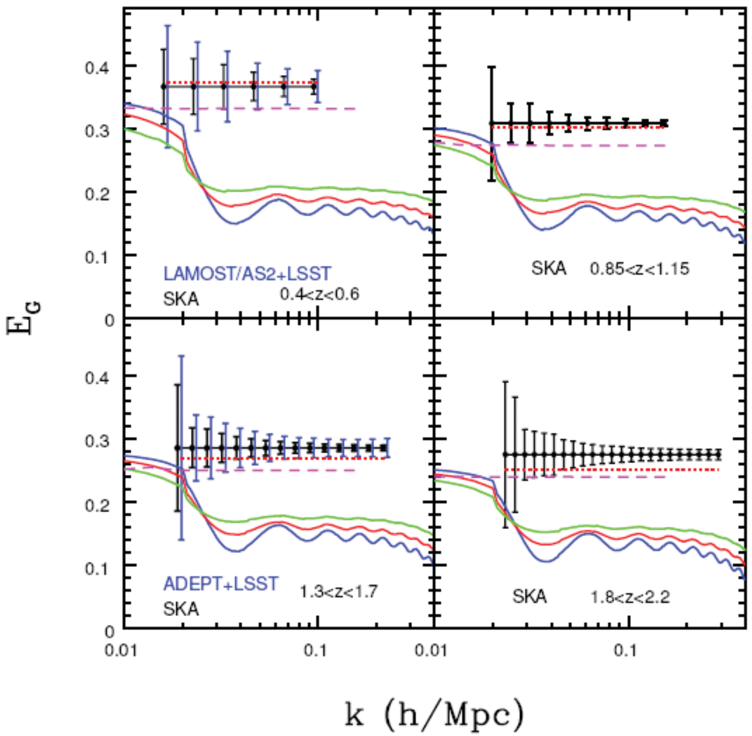
Acquaviva et al. 2008

RSD+weak lensing to test GR

Weak lensing

$$E_G = \frac{\text{时空扰动}}{\text{物质扰动}} = \frac{\Omega_0}{f}\frac{G_{\rm eff}}{G_{\rm Newton}}$$

RSD



- ✧ **Solar system test： 10^{-4} ly**
- ✧ **E_G： 10^{8} ly**

ZPJ+，2007，PRL

Existing E_G measurement： consistent with GR

Redshift	E_G	Survey/reference
z=0.32	0.39±0.06	SDSS (Reyes+, 2010)
	0.48±0.10	CFHTLenS/RCSLenS+WiggleZ/BOSS (Blake+ 2016)
z=0.57	0.30±0.07	CFHTLenS/RCSLenS+WiggleZ/BOSS (Blake+ 2016)
	0.24±0.06	Planck CMB lensing+BOSS(Pullen+ 2016). ~2.6sigma tension with GR
	0.42±0.06	CFHTLenS+BOSS（Alam +, 2016)
z=0.6	0.16±0.09	CFHTLenS+VIPERS (de la Torre+, 2016)
z=0.8	0.09±0.07	CFHTLenS+VIPERS (de la Torre+, 2016)

Cosmological constant or dynamical dark energy?

(1) curvature?
(2) Weak violation of the Copernican Principle?

Existing constraints on w(z)

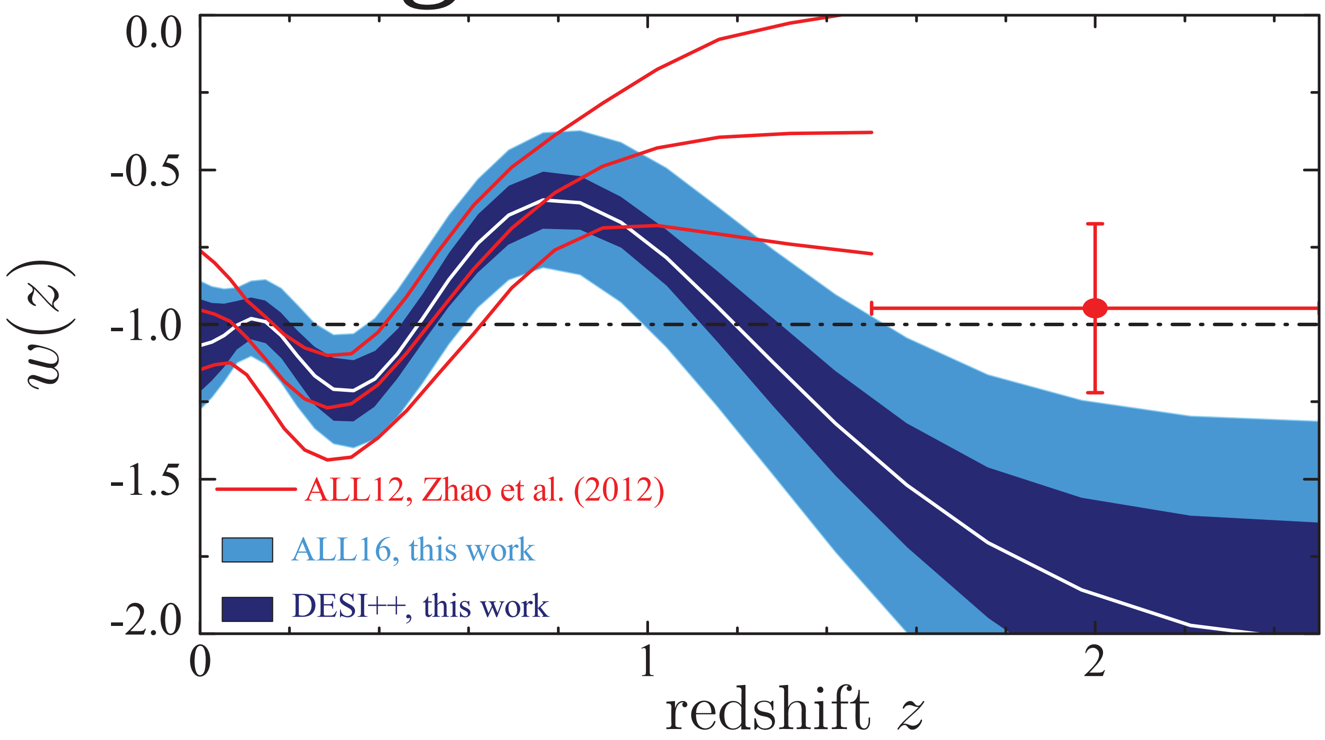
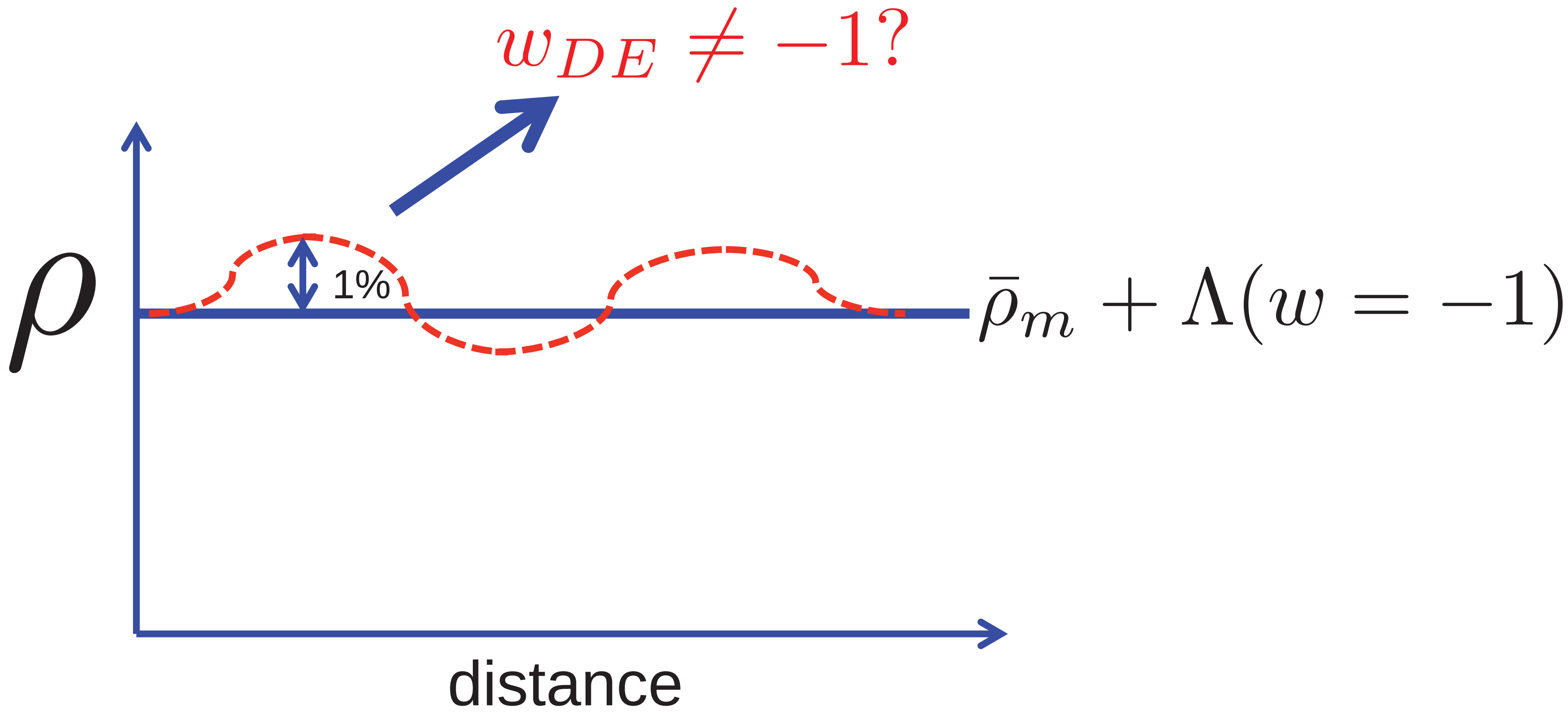


FIG. 5. The mean and the 68% CL uncertainty of the $w(z)$ reconstructed from ALL16 (light blue) compared to the ALL12 $w(z)$ reconstructed in [27] (red lines showing the mean and the 68% CL band). The red point with error bars is the value of $w(z)$ at $z = 2$ "predicted" by the ALL12 reconstruction. The dark blue band around the ALL16 reconstruction is the forecasted 68% CL uncertainty from DESI++.

Zhao +, 2017

Weak violation of the Copernican Principle can bias CC into DE or vice versa



The linear kSZ test constrains that the expansion rate is uniform at 1% level to the horizon

$$\frac{\delta\rho}{\rho} = 2\frac{\delta H}{H} \lesssim 1\%$$

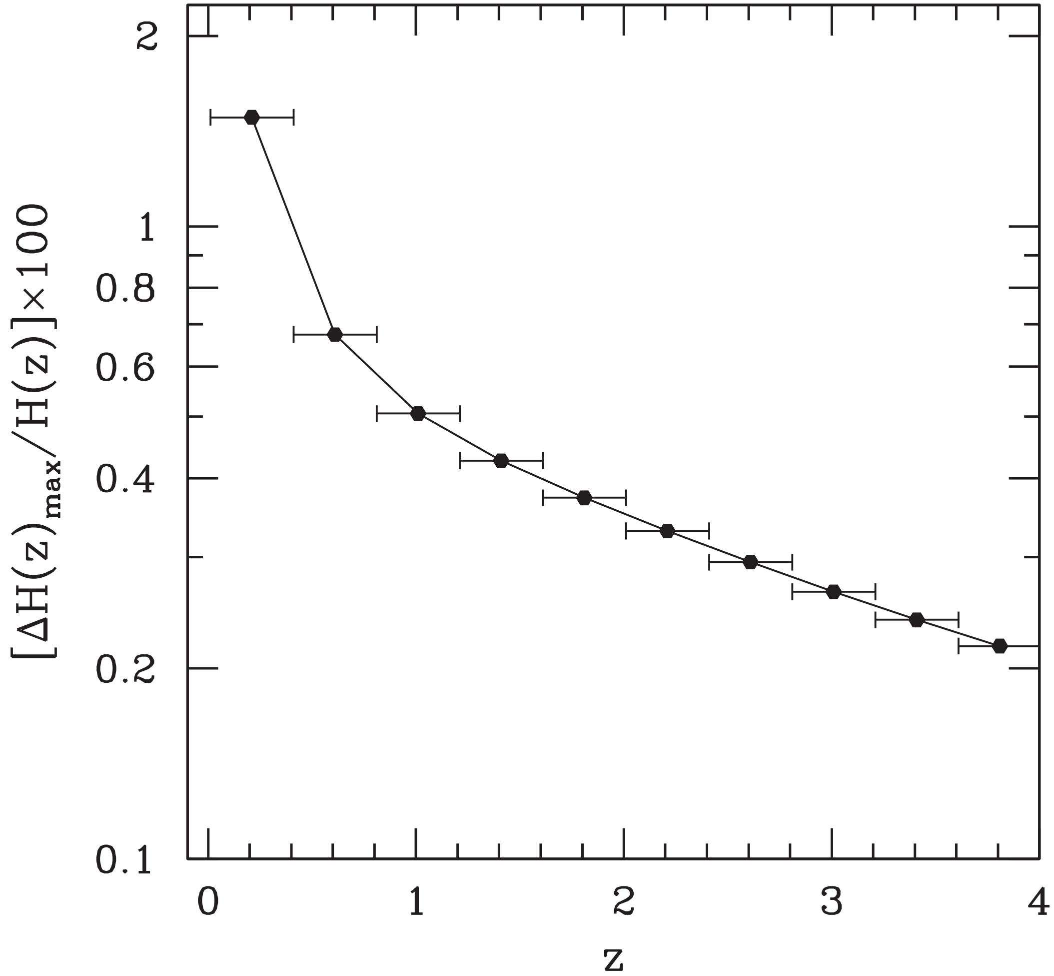


FIG. 2. The maximal deviation from the overall expansion allowed by the SPT observation, for each mass shell of $\Delta z = 0.4$, which corresponds to $1h^{-1}$ Gpc at $z \sim 0$, $0.7h^{-1}$ Gpc at $z \sim 1$, and $0.5h^{-1}$ Gpc at ~ 2.

ZPJ & Stebbins, 2011， PRL