DARK ENERGY

Universenet Mid-term Review

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Outline

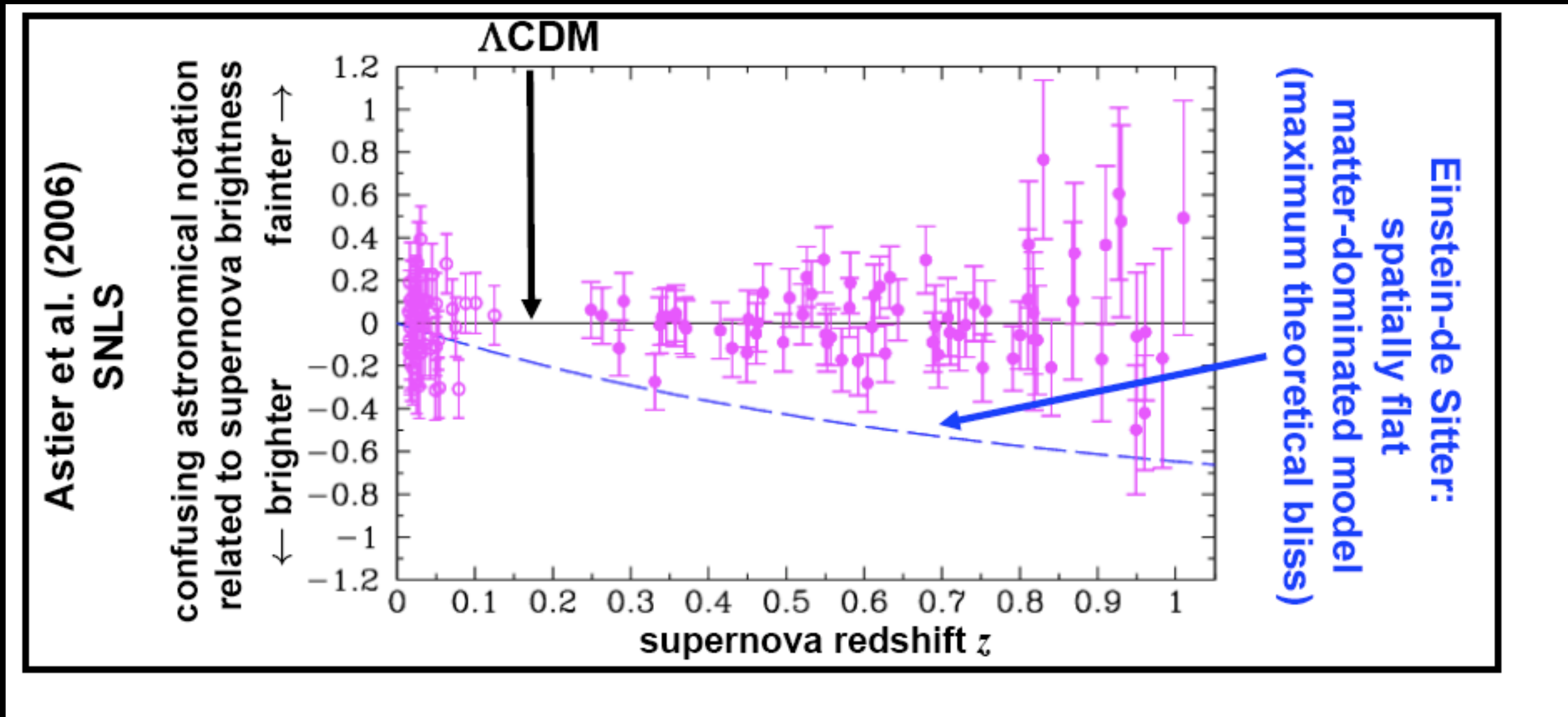
- Short introduction and motivation for DE
- Is it really DE? Possible alternatives (modified gravity, anthropic principle, inhomogeneous Universe)
- Strategies to distinguish various explanations
- Conclusions

Emphasis on network activities

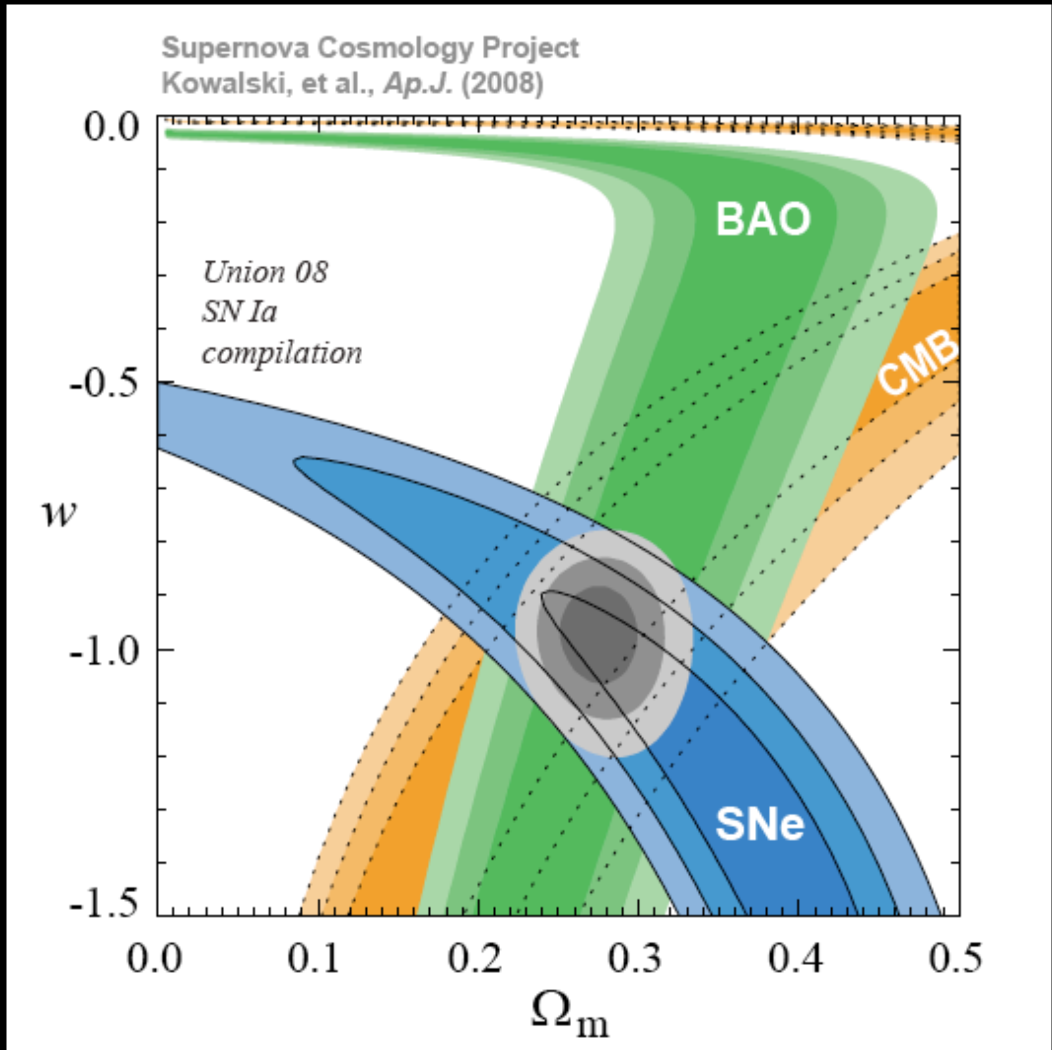
The Universe is accelerating

$$d_L(z) = \frac{1}{H_0}\left[z + (1-q_0)\frac{z^2}{2} + \left(-j_0 + 3q_0^2 - 1 - \frac{k}{a_0^2 H_0^2}\right)\frac{z^3}{6} + \mathcal{O}(z^4)\right.$$

$$q \equiv -(\ddot{a}/a)/H^2, \text{ jerk } j \equiv (\dddot{a}/a)/H^3$$

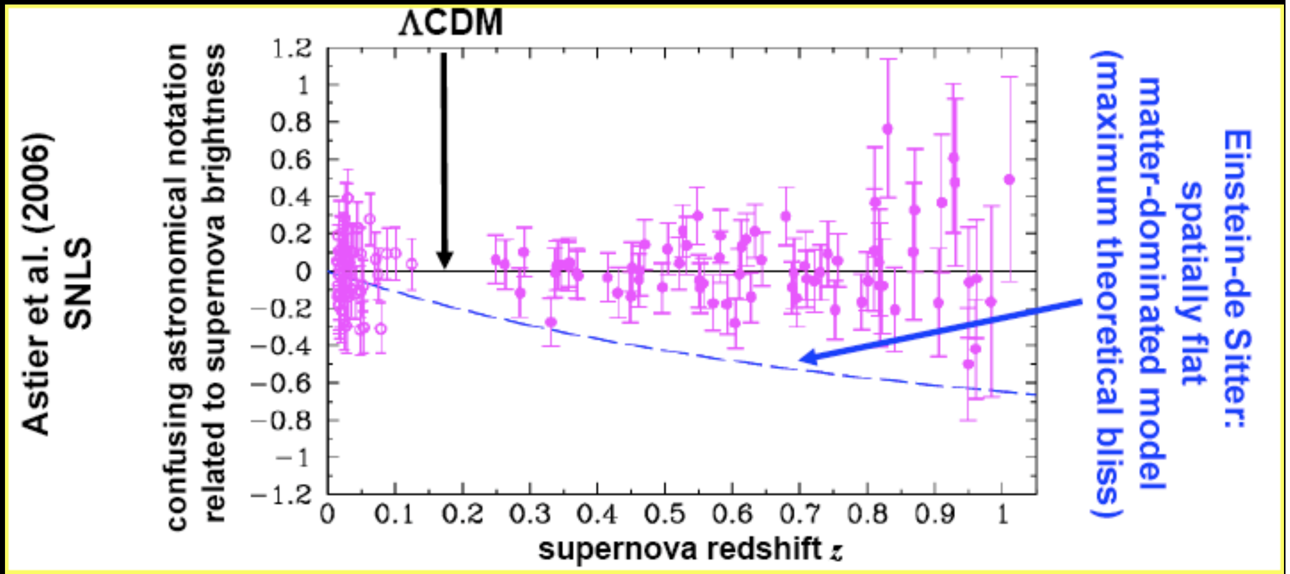


Fluid with $P/\rho = w$ implies $q < 0$ if $(1 + 3w) < 0$

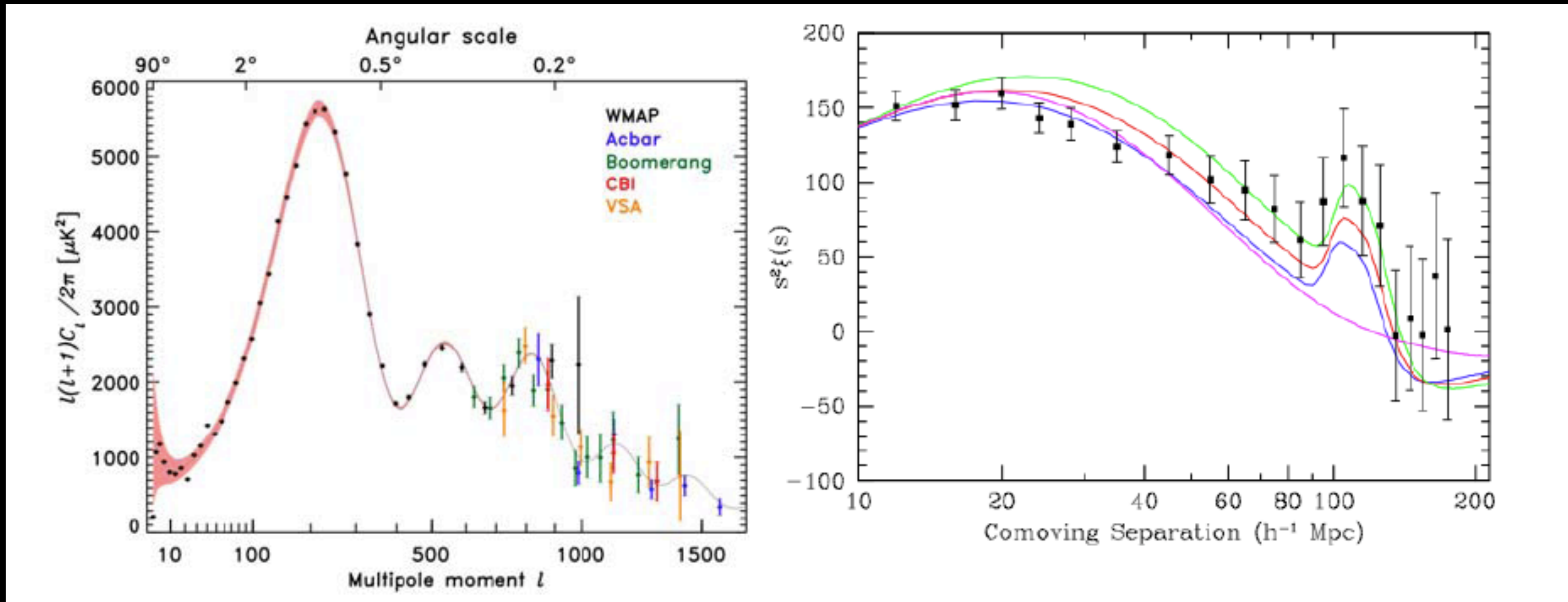


Evidence for Dark Energy

- Hubble Diagram (SNe)
- Baryon acoustic oscillations
- Weak lensing
- Galaxy clusters
- Age of the Universe
- Structure formation



Acustic Baryonic Oscillations



Each overdense region is an overpressure that launches a spherical sound wave.
Wave travels outward at sound speed.
Photons decouple, travel to us and are observable as CMB acoustic peaks. For matter, sound speed plummets, wave stalls, total distance travelled 150 Mpcimprinted on power spectrum.
DE enters in the determination of the angular distance

How do we know DE exists?

- Assume FRW model of cosmology: $H^2 = 8\pi G\rho/3 - k/a^2$
- Assume energy and pressure content: $\rho = \rho_M + \rho_\gamma + \rho_\Lambda + \cdots$
- Input cosmological parameters
- Compute observables: $d_L(z),\ d_A(z),\ H(z)$
- Model cosmology fits with ρ_Λ , but not without ρ_Λ
- All evidence for DE is INDIRECT : the observed Hubble rate is not the one predicted through all the previous steps

Taking sides:

$$G_{00}(\mathrm{FRW}) = 8\pi\, G\, T_{00}$$

1) Modify the RHS of Einstein equations

- a) Cosmological constant
- b) Not constant (scalar field)

2) Modify the LHS of Einstein equations

- a) Beyond Einstein (mod. of gravity)
- b) Just Einstein (BR of inhomog.)

Modify the RHS: CC/Quintessence

- Many possible contributions? Stringy?

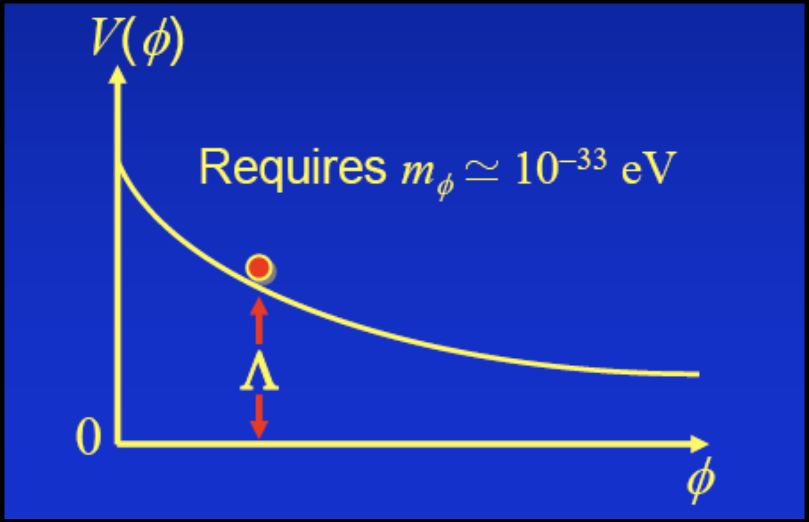
  N.E. Mavromatos et al. 2007

- Why then is the total so small? Seesaw-like like mechanism?

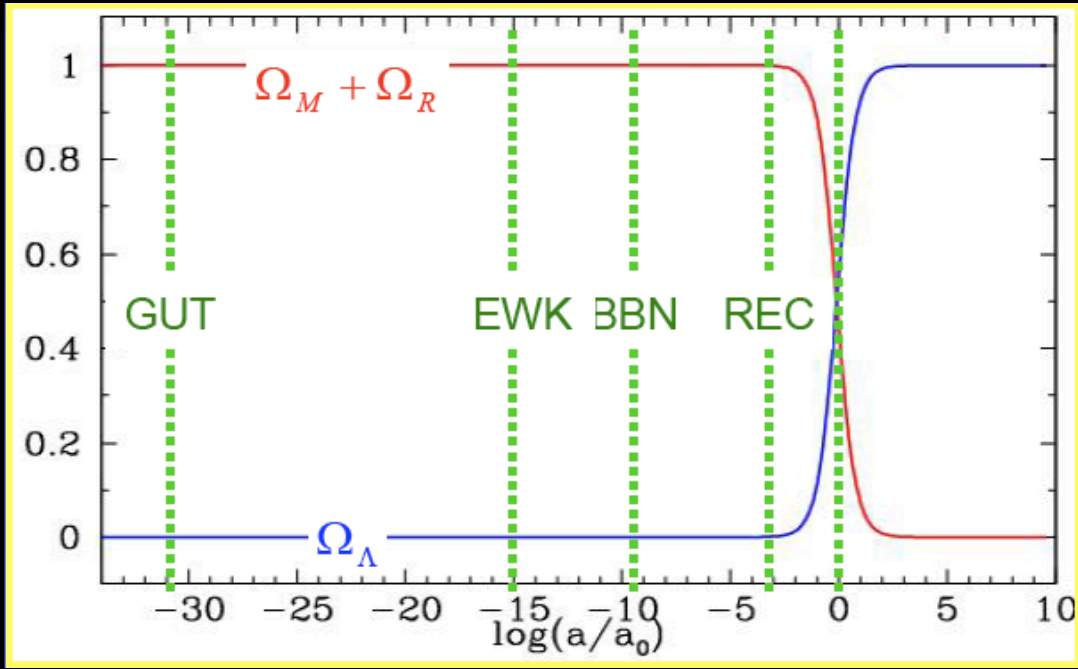
  K. Enqvist, S. Hannestad & M. Sloth, 2007

- Lorentz violating DE?

  L. Papantonopoulos, V. Rubakov et al., 2007



Why now?



- Mass Varying Neutrino models: $V^{1/4} \sim m_\nu \sim \left(10^{-3}\right)\ \mathrm{eV}$

O. Bjaelde, S. Hannestad et al., 2006

- Scalar-tensor theories: modification of pre-DE era

A. Masiero, M. Pietroni, R. Catena, 2006

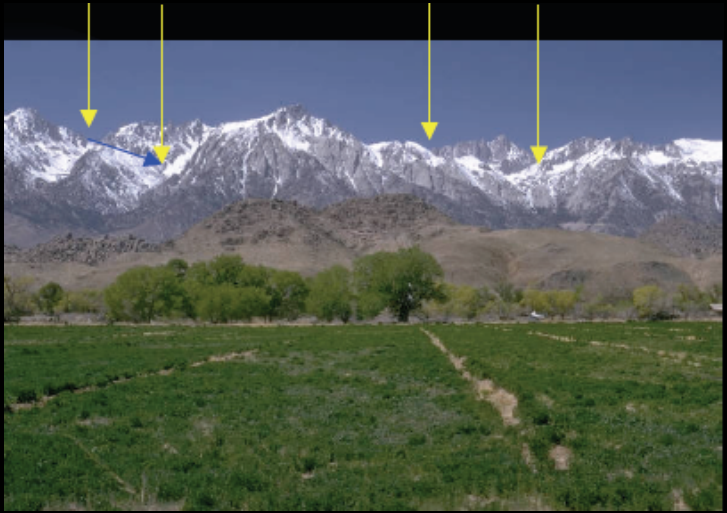
Anthropic/Landscape

- Many sources of vacuum energy
- String Theory has many vacua $> 10^{500}$
- Some of them correspond to a cancellation leading to the observed small cosmological constant

Galaxies require (Weinberg)

$$\Lambda < 10^{-118}\, M_{\rm Pl}^4$$

- Although the are exponentially uncommon, they are preferred because...
- More common values of the CC results in an inhospitable Universe



How are these vacua populated in the eternal inflation picture?
Dynamical selection principle

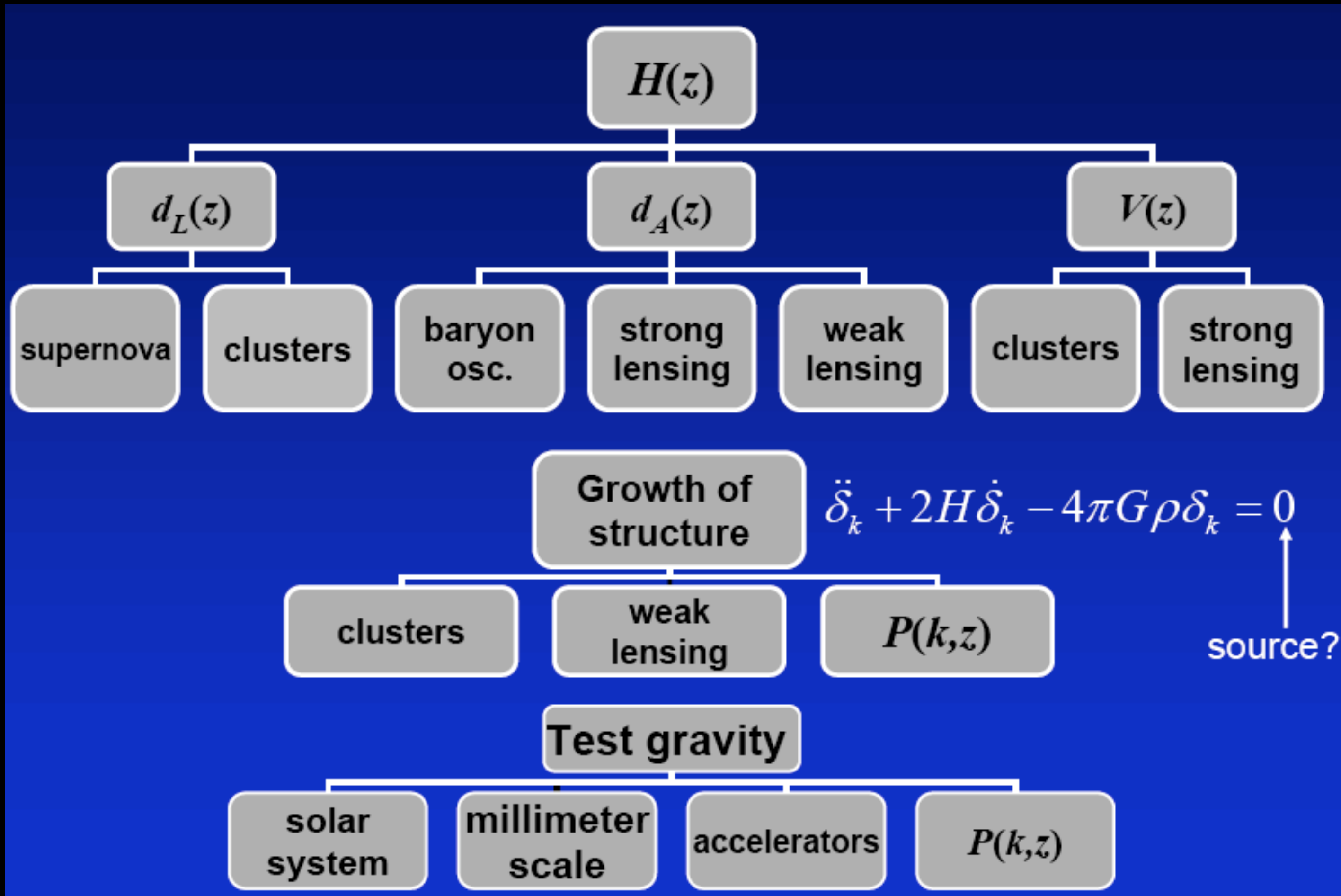
D. Podolsky and K. Enqvist, 2007

Modify the LHS: non-standard gravity

$$G_{\mathrm{N}}^{-1}\left(L^2\Box\right)G_{\mu\nu} = 8\,\pi\,T_{\mu\nu}$$

At distances $\gg L$ gravity becomes weaker

Observational strategy



Cosmological Perturbations are sensitive to energy content

$$\ddot{\delta}_m + 2H\dot{\delta}_m = \frac{3}{2}H^2\delta_m, \;\; \delta_m = \delta\rho_m/\rho_m$$

Perturbations can be probed at different epochs:

1) CMB, z ~ 1100
2) 21 cm, z ~ 10-20
3) Ly-alpha forest, z ~ 2-4
4) Weak lensing, z ~ 0.3-2
5) Galaxy clustering, z ~ 0-2

Growth function vs data

$$f = \frac{d \ln \delta_m}{d \ln a}$$

Redshift distortion parameter observed through the anisotropic pattern of galactic redshifts on cluster scales

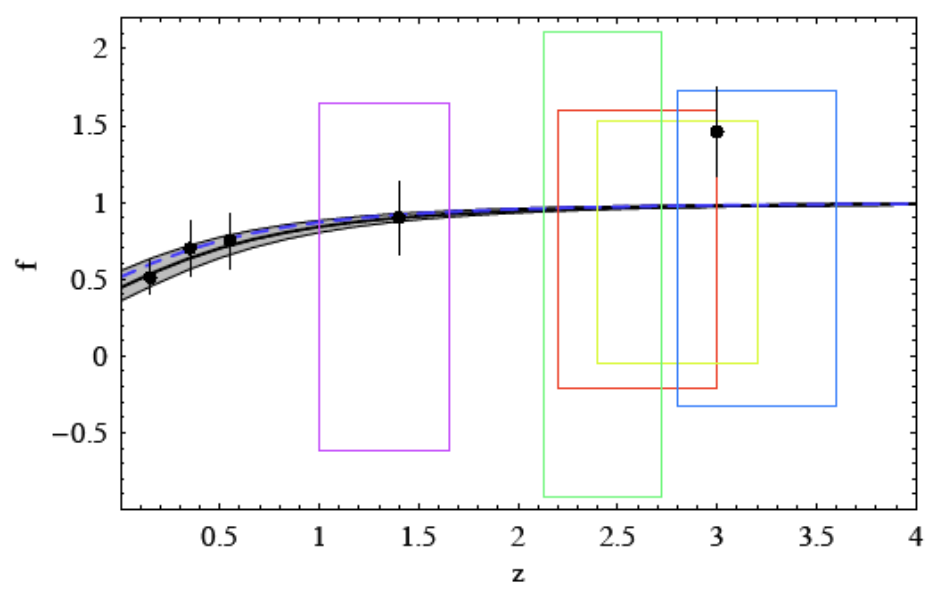


FIG. 2: The cosmological data for the growth rate $f(z)$ along with the best theoretical fit $f = \Omega_m(z)^\gamma$ with $\Omega_{0m} = 0.3$ (black continuous line) and the corresponding 1σ errors (shaded region). The errorboxes on f are obtained using the ratios at the specific redshifts. Clearly, the best fit shows a minor difference from ΛCDM (blue dashed line) only at low redshifts.

S. Nesseris & L. Perivolaropoulos, 2007

The effect of DE perturbations

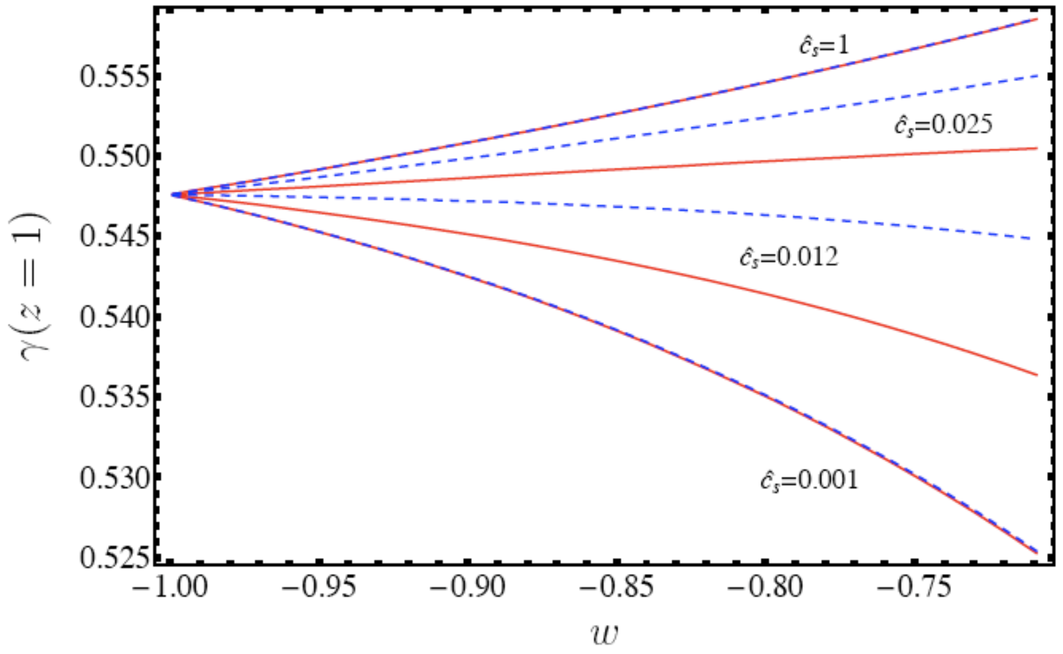


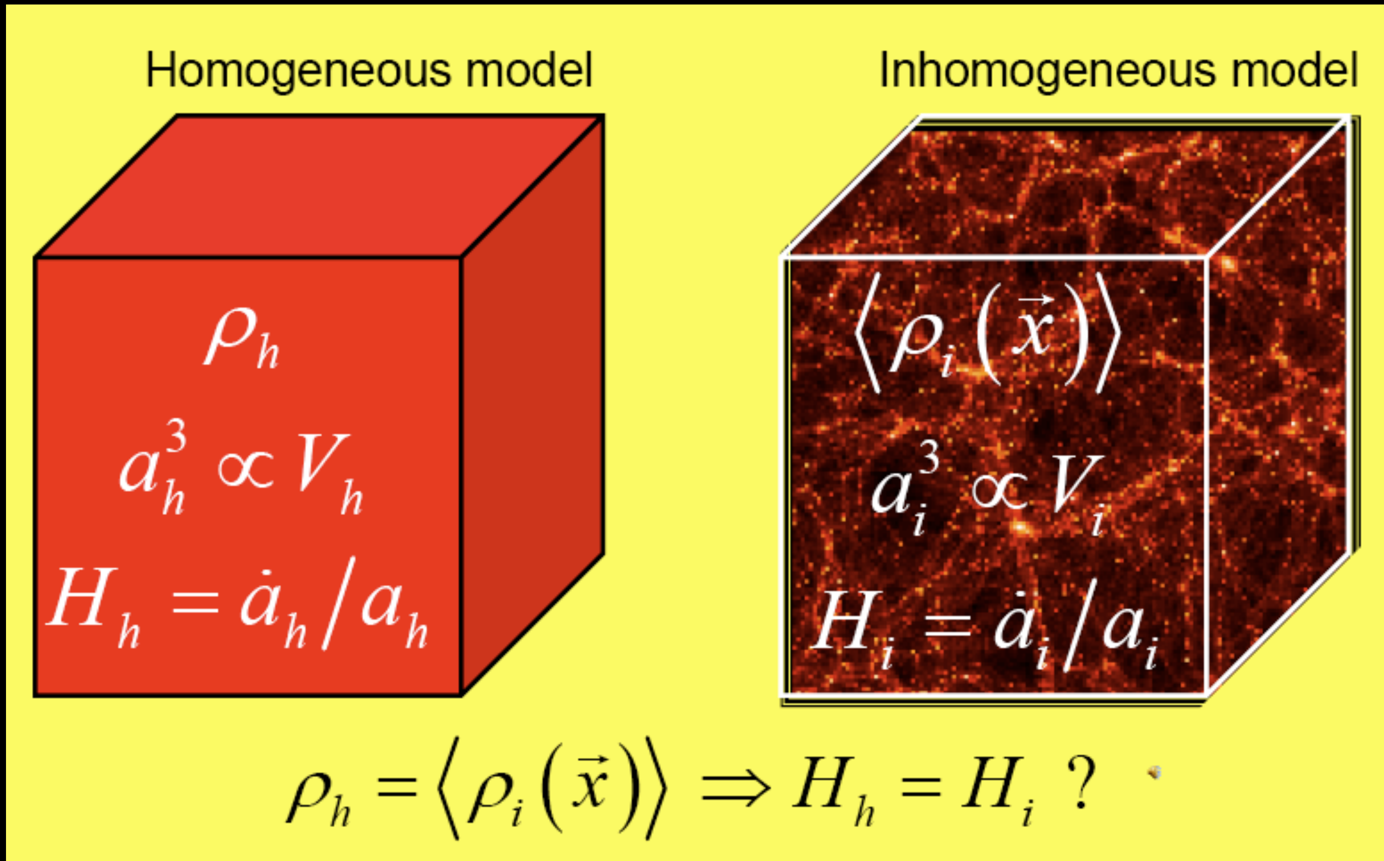
Figure 1: $\gamma(z = 1)$ as a function of w is shown for four values of $\hat{c}_s$. Red curves correspond to $k = 0.050\,h\mathrm{Mpc}^{-1}$ and blue dashed ones to $k = 0.078\,h\mathrm{Mpc}^{-1}$.

$$g(a) \equiv \delta_m/a = e^{\int_0^a d\ln a' \left[\Omega_M^\gamma(a')-1\right]}$$

$$\gamma_{\rm mod\ grav} \simeq 0.68$$

G. Ballesteros & A.R., 2008

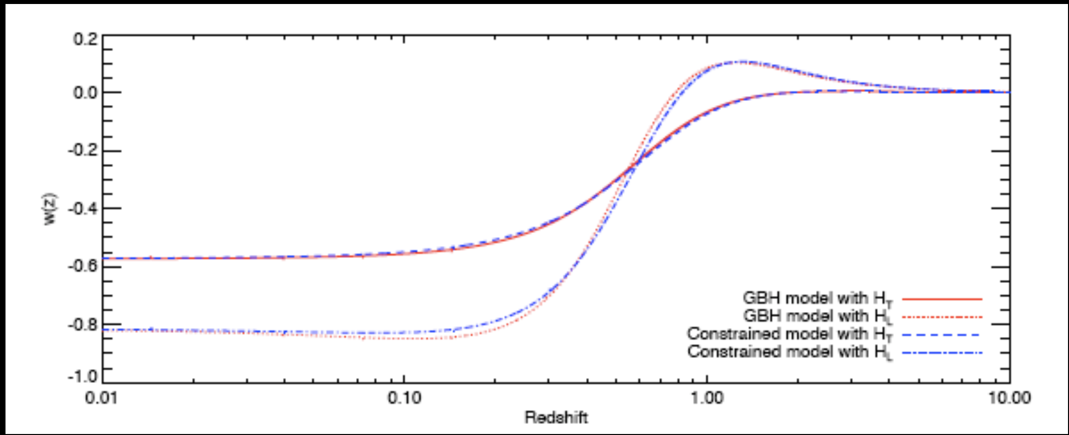
Modify the LHS: local inhomogeneities



K. Enqvist, J. Garcia-Bellido, T. Haugbolle, P. Hunt, T. Mattsson, A. Notari, S. Rasanen, A.R., S. Sarkar, ...

Lemaitre-Tolman-Bondi Models

- Spherical model
- Overall Einstein-de Sitter
- Inner underdense void of size ~100 Mpc
- Calculate $d_L(z)$
- Compare to data
- Fit with $\Lambda = 0$



J. Garcia-Bellido & T. Haugbolle, 2008

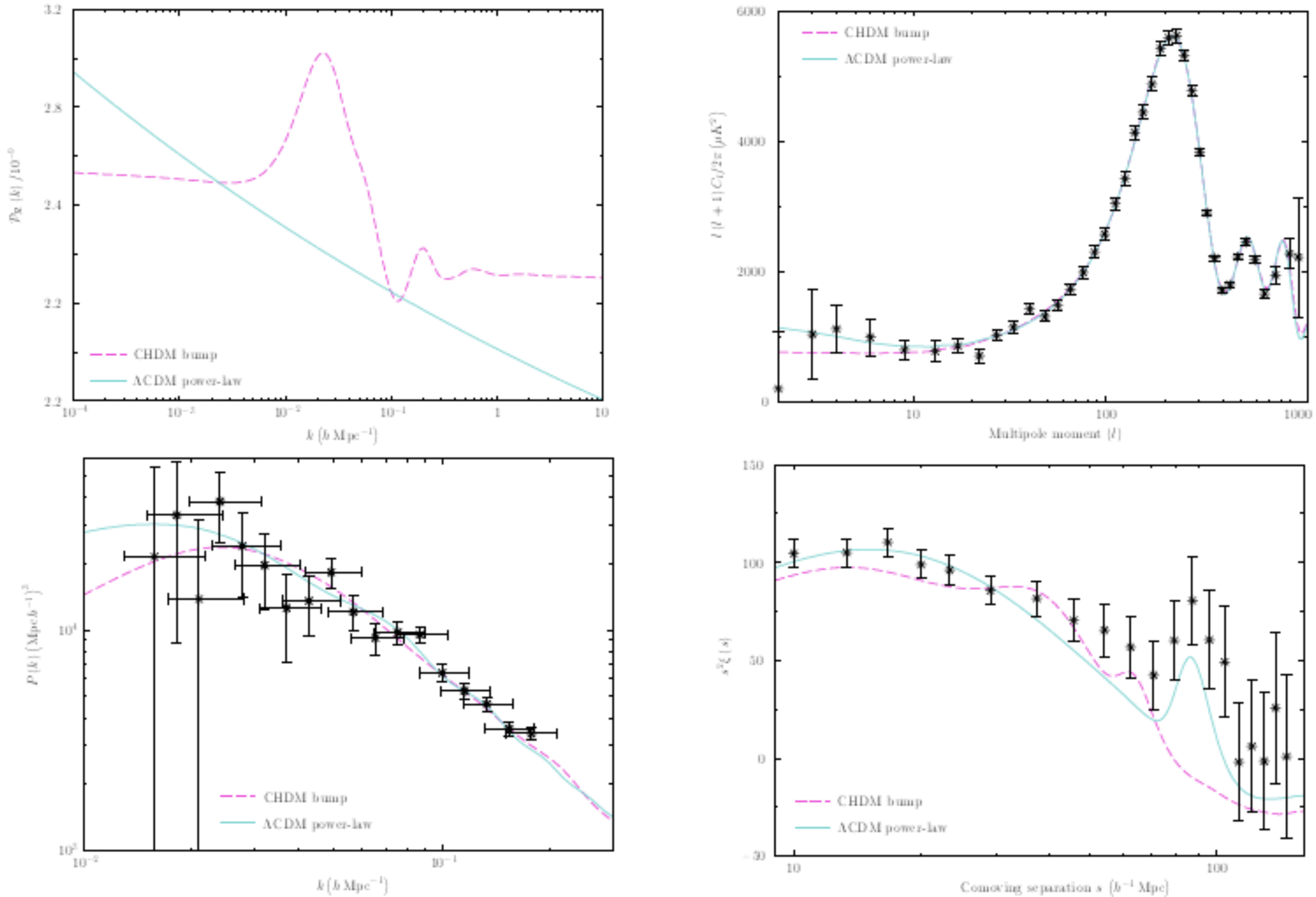


Fig. 5 Comparison of the power law ΛCDM model and the alternative CHDM model with a 'bump' in the primordial spectrum (top left); the *WMAP* data (top right) and *SDSS* data (bottom left) are equally well-fitted, but the BAO peak in the LRG correlation function (bottom right) favours ΛCDM [41].

T. Haugbolle, P. Hunt & S. Sarkar, 2007

Conclusions

- The origin of the acceleration of the Universe is still a mistery
- The members of the Universenet teams are very actively contributing to the field with theoretical and phenomenological studies
- The Universe is dark, but the future is brighter