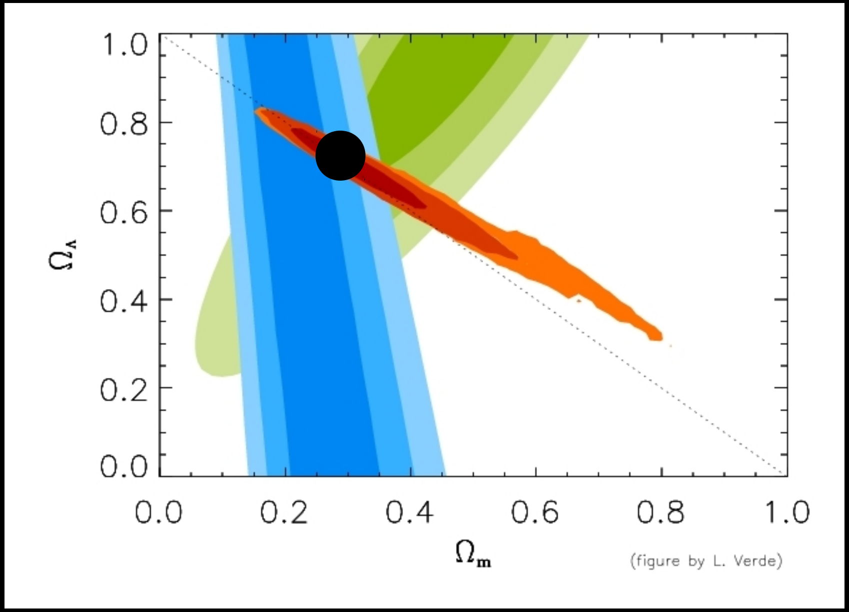
Observations are converging…



…to an unexpected universe

Classifying the unknown, 1

1. Cosmological constant
2. Dark energy w=const
3. Dark energy w=w(z)
4. quintessence
5. scalar-tensor models
6. coupled quintessence
7. mass varying neutrinos
8. k-essence
9. Chaplygin gas
10. Cardassian
11. quartessence
12. quiescence
13. phantoms
14. f(R)
15. Gauss-Bonnet
16. anisotropic dark energy
17. brane dark energy
18. backreaction
19. void models
20. degravitation
21. TeVeS
22. oops....did I forget *your* model?

Classifying the unknown, 3

Standard cosmology:
GR gravitational equations + symmetries

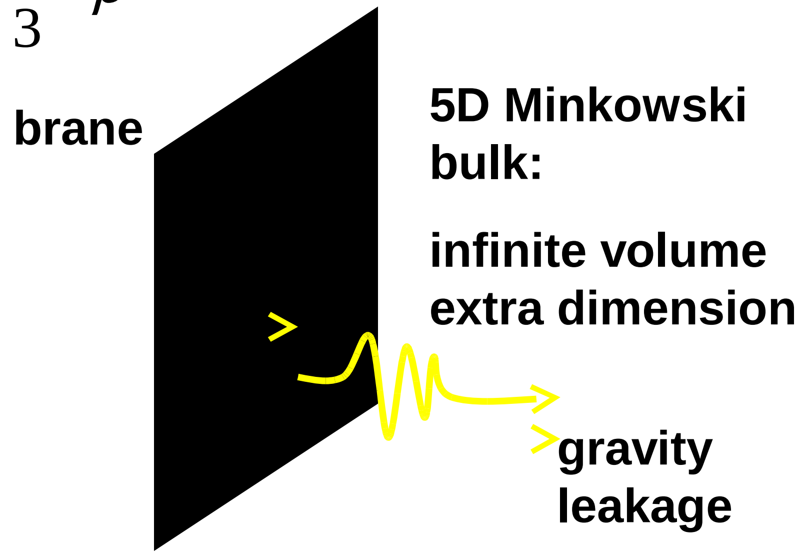
a) change the equations
i.e. add new matter field (DE) or modify gravity (MG)
b) change the symmetries
i.e. inhomogeneous non-linear effects, void models, etc

Simplest MG (I): DGP

(Dvali, Gabadadze, Porrati 2000)

$$S = \int d^5x\sqrt{-g^{(5)}}\; R^{(5)} \;+\; L\int d^4x\sqrt{-g}\,R$$

$$H^2 - \frac{H}{L} = \frac{8\pi G}{3}\rho$$



L = crossover scale:

$$r << L \Rightarrow V \propto \frac{1}{r}$$

$$r >> L \Rightarrow V \propto \frac{1}{r^2}$$

- **5D gravity dominates at low energy/late times/large scales**
- **4D gravity recovered at high energy/early times/small scales**

Simplest MG (II): f(R)

The simplest MG in 4D: f(R)

$$\int dx^4 \sqrt{g}\left[f\left(R\right) + L_{matter} \right]$$

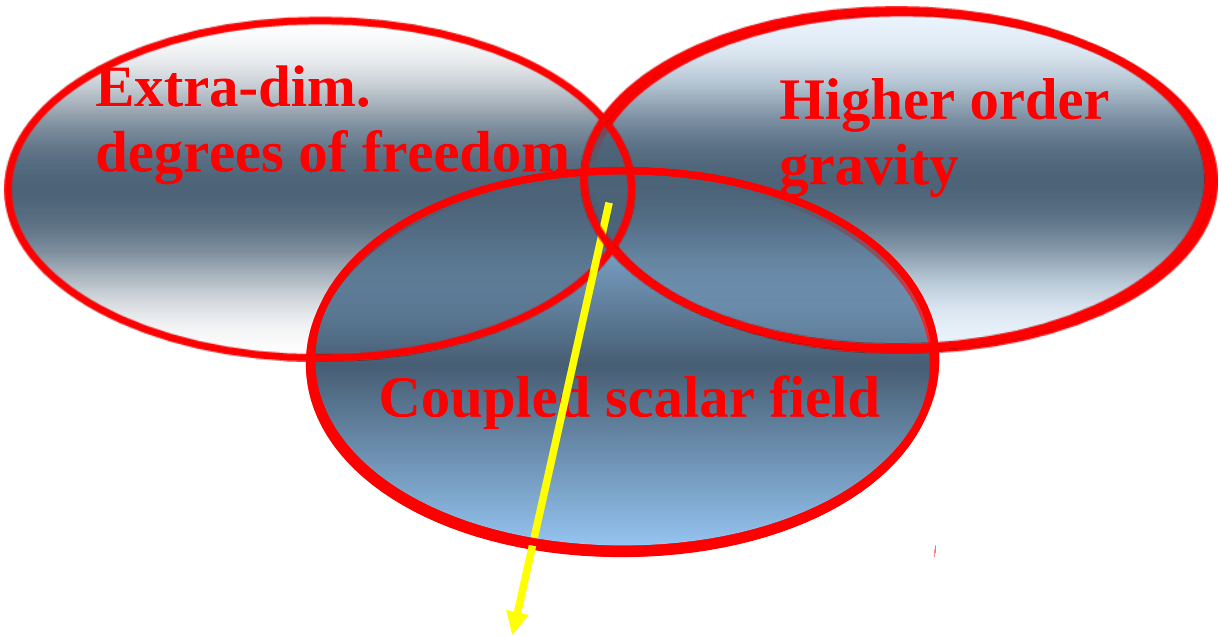
eg higher order corrections

$$\int dx^4 \sqrt{g}\left(R + R^2 + R^3 + \ldots\right)$$

- ✓ f(R) models are simple and self-contained (no need of potentials)
- ✓ easy to produce acceleration (first inflationary model)
- ✓ high-energy corrections to gravity likely to introduce higher-order terms
- ✓ particular case of scalar-tensor and extra-dimensional theory

Faces of the same physics

physics



$$\int dx^4 \sqrt{g}\left[f\left(\varphi, R\right) + L_{matter} \right]$$

Scalar-tensor gravity

Is this already ruled out by local gravity?

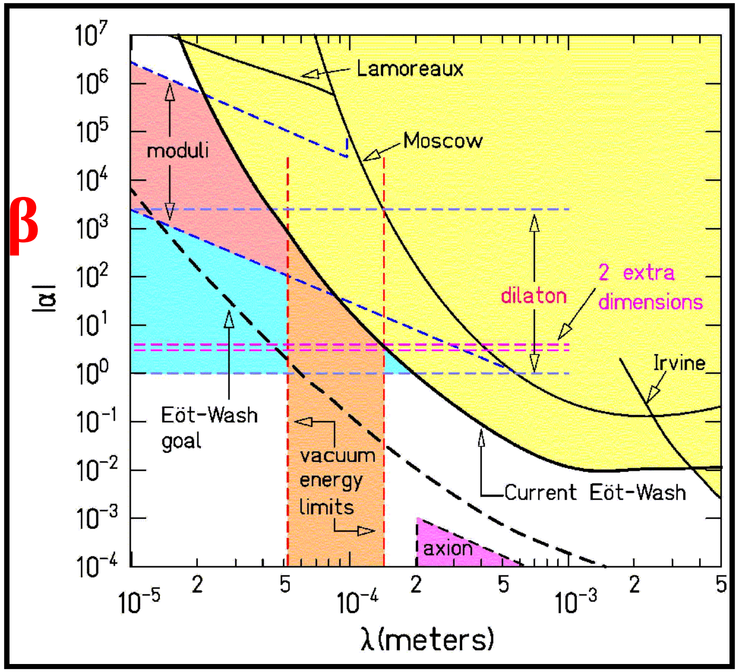
$$\int dx^4 \sqrt{g}\,(f(R) + L_{matter})$$

is a scalar-tensor theory with Brans-Dicke parameter ω=0 or
a coupled dark energy model with coupling β=1/2

$$G^* = G(1+\beta^2 e^{-m_\varphi r}) = G(1+\beta^2 e^{-r/\lambda})$$

$$m^2_\varphi \sim \frac{1}{f''}$$

β



Adelberger et al. 2005

The fourfold way out of local constraints

$$G^* = G(1+\beta^2 e^{-m_\varphi r})$$

$$m_\phi, \beta \left\{ \begin{array}{l} \text{depend on time} \\ \text{depend on space} \\ \text{depend on local density} \\ \text{depend on species} \end{array} \right.$$

The simplest case

$$\int dx^4 \sqrt{g}\left(R - \frac{\mu^4}{R} + L_{matter} \right)$$

Turner, Carroll, Capozziello etc. 2003

In Einstein Frame

$$\hat{g}_{\mu\nu} = (f')^2 g_{\mu\nu}$$

$$\ddot{\phi} + 3H\dot{\phi} + V(\phi)' = \frac{\sqrt{3}}{2}\beta\rho_m$$

$$\ddot{\phi} + 3H\dot{\phi} + V(\phi)' = 0$$

$$V(\phi)' = \frac{fR - f'}{f'^2}$$

$$\dot{\rho}_m + 3H\rho_m = 0$$

$$\dot{\rho}_m + 3H\rho_m = -\frac{\sqrt{3}}{2}\beta\dot{\phi}\rho_m$$

$$\phi = \log f'$$

$$\beta = 1/2$$

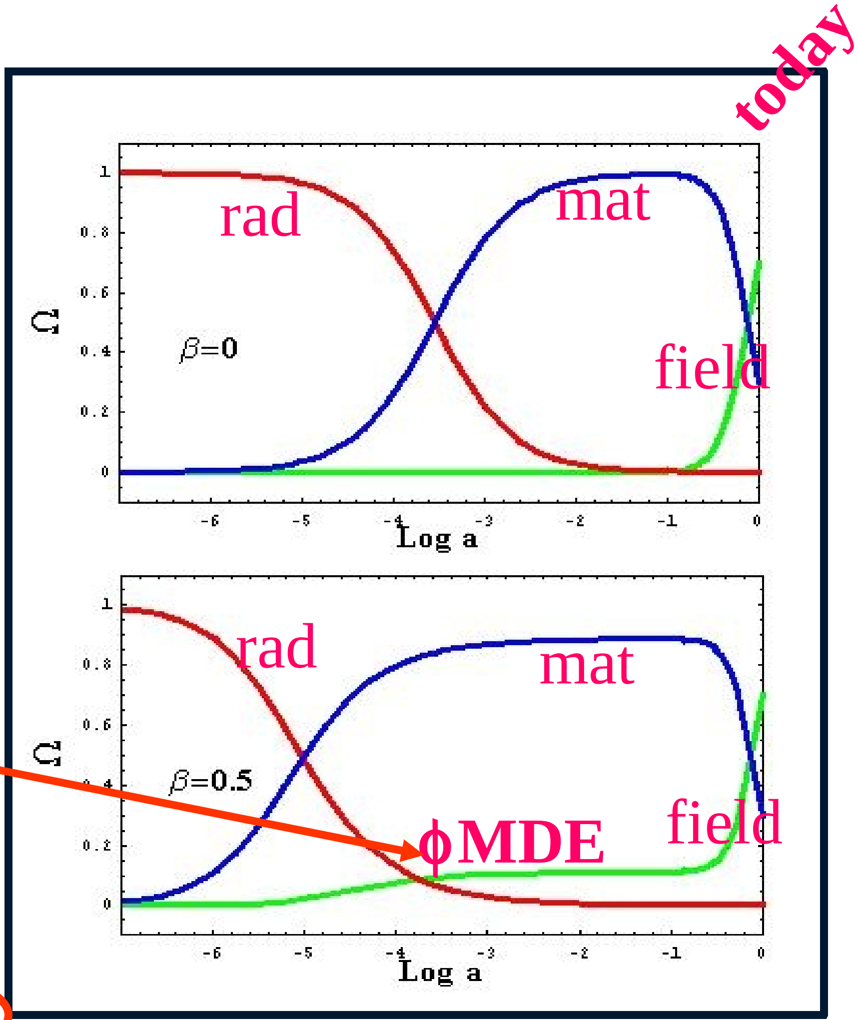
…a particular case of coupled dark energy

R-1/R model : the φMDE

$$\ddot{\phi}+3H\dot{\phi}+V(\phi)'=\frac{\sqrt{3}}{2}\beta\rho_m$$

$$\dot{\rho}_m+3H\rho_m=-\frac{\sqrt{3}}{2}\beta\dot{\phi}\rho_m$$

$$H^2=\frac{8\pi}{3}(\rho_m+\rho_\phi)$$



$$\beta=1/2$$

$$\Omega_\varphi=1/9$$

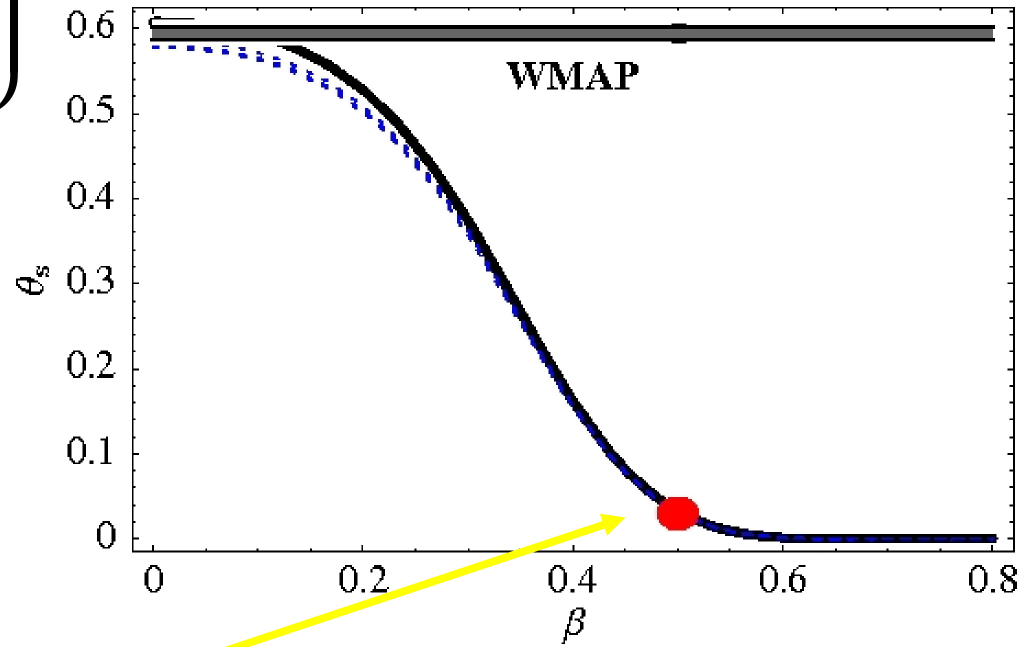
In Jordan frame: $a=t^{1/2}$

instead of $a=t^{2/3}$!!

Caution: Plots in the Einstein frame!

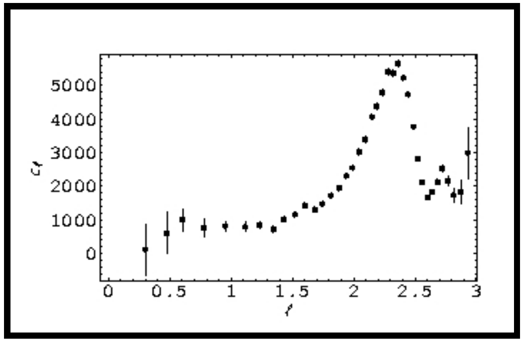
Sound horizon in R+R $^{-n}$ model

$$\int dx^4 \sqrt{g}\left(R - \frac{\mu^4}{R} + L_{matter} \right)$$



$a \approx t^{1/2}$ in the Matter Era !

$$\theta = \int_{z_{dec}}^{\infty} \frac{c_s dz}{H(z)} \Big/ \int_{0}^{z_{dec}} \frac{dz}{H(z)}$$



L.A., D. Polarski, S. Tsujikawa, PRL 98, 131302, astro-ph/0603173

A recipe to modify gravity

Can we find f(R) models that work?

LGC+Cosmology

Take for instance the ΛCDM clone

$$f(R) = (R^a - \Lambda)^b$$

Applying the criteria of
LGC and background cosmology

$$a \approx b \approx 1 \pm 10^{-23}$$

i.e. ΛCDM to an incredible precision

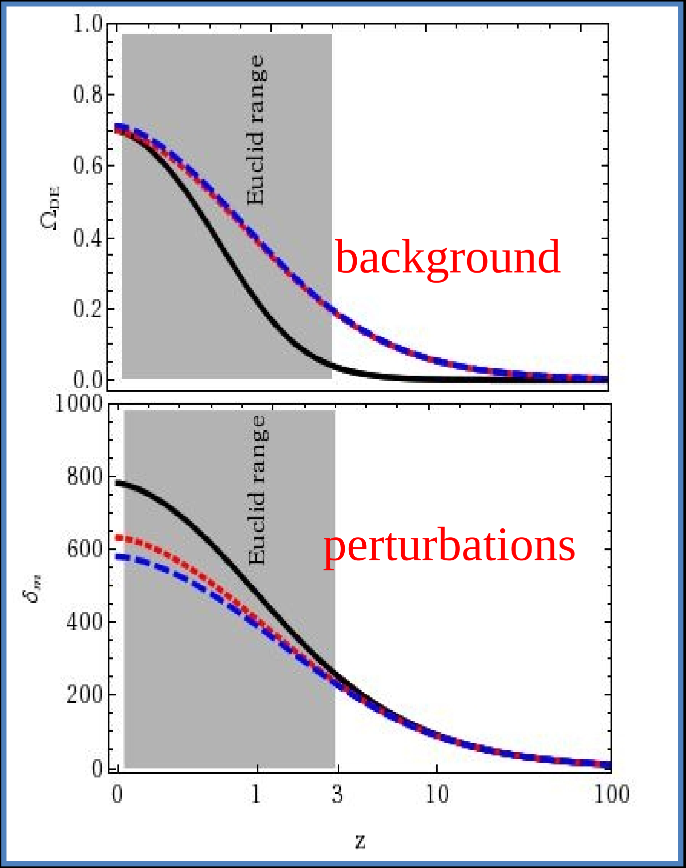
Space-time geometry

The most general (linear, scalar) metric at first-order

$$ds^2 = a^2[(1+2\Psi)dt^2 - (1+2\Phi)(dx^2 + dy^2 + dz^2)]$$

Full metric reconstruction
at first order requires 3 functions

$$H(z) \quad \Phi(k,z) \quad \Psi(k,z)$$



Two free functions

At linear order we can write:

- Poisson equation

- zero anisotropic stress

Two free functions

At linear order we can write:

- modified Poisson equation $Q(k,a)$

- non-zero anisotropic stress $\eta(k,a)$

Modified Gravity at the linear level

- standard gravity

$$Q(k,a)=1$$
$$\eta(k,a)=0$$

- scalar-tensor models

$$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{2(F+F'^2)}{2F+3F'^2}$$
$$\eta(a)=\frac{F'^2}{F+F'^2}$$

Boisseau et al. 2000
Acquaviva et al. 2004
Schimd et al. 2004
L.A., Kunz &Sapone 2007

- f(R)

$$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{1+4m\frac{k^2}{a^2R}}{1+3m\frac{k^2}{a^2R}},\quad \eta(a)=\frac{m\frac{k^2}{a^2R}}{1+2m\frac{k^2}{a^2R}}$$

Bean et al. 2006
Hu et al. 2006
Tsujikawa 2007

- DGP

$$Q(a)=1-\frac{1}{3\beta};\quad \beta=1+2Hr_c w_{DE}$$
$$\eta(a)=\frac{2}{3\beta-1}$$

Lue et al. 2004;
Koyama et al. 2006

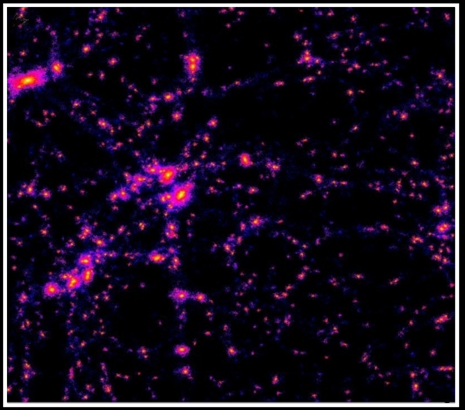
- coupled Gauss-Bonnet

$$Q(a)=\ldots$$
$$\eta(a)=\ldots$$

see L. A., C. Charmousis, S. Davis 2006

Reconstruction of the metric

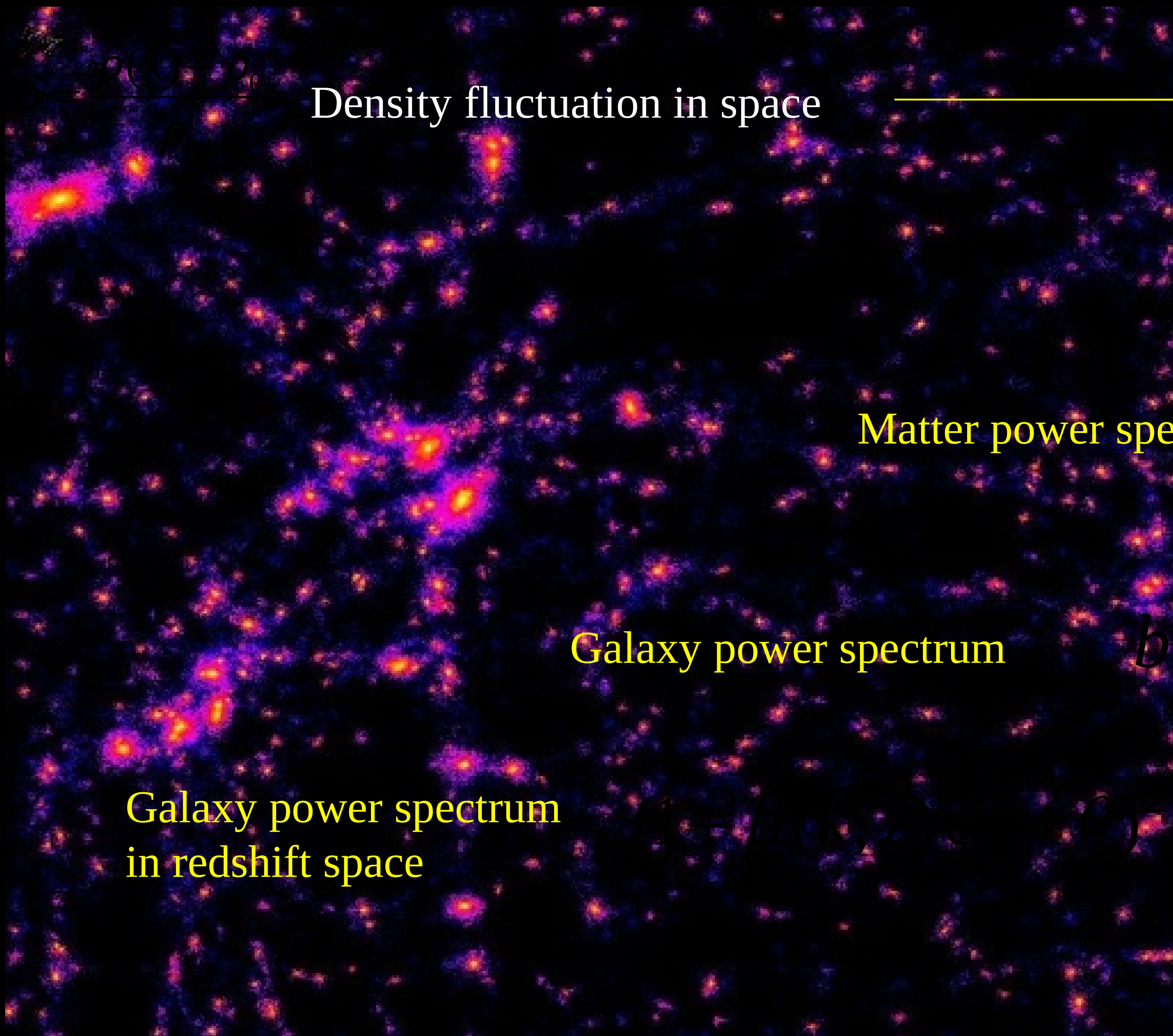
$$ds^2 = a^2[(1+2\Psi)dt^2 - (1+2\Phi)(dx^2 + dy^2 + dz^2)]$$



massive particles respond to Ψ

massless particles respond to Φ-Ψ

Reality check



Density fluctuation in space

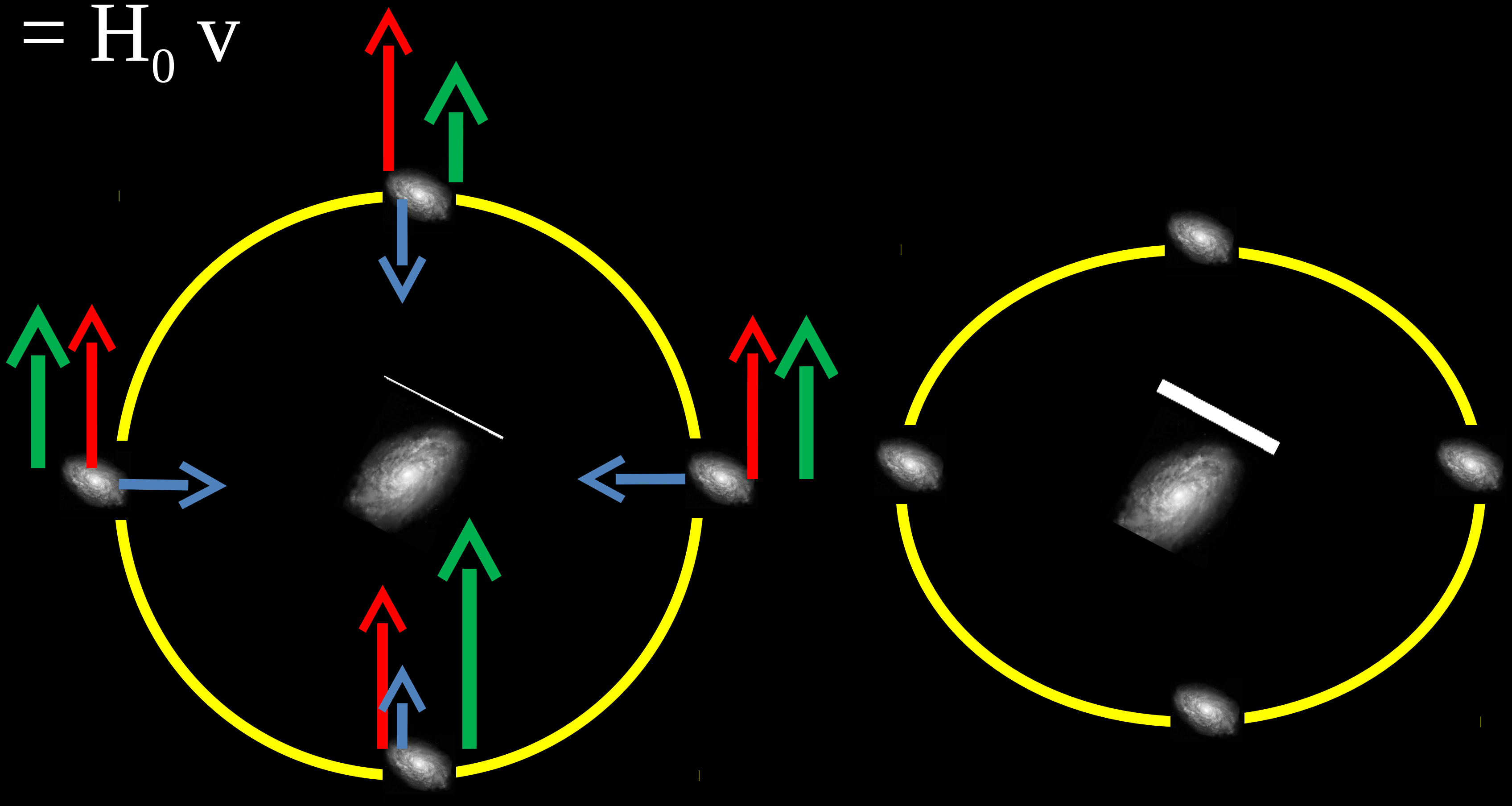
Matter power spectrum

Galaxy power spectrum

Galaxy power spectrum
in redshift space

Peculiar velocities

$r = H_0 v$



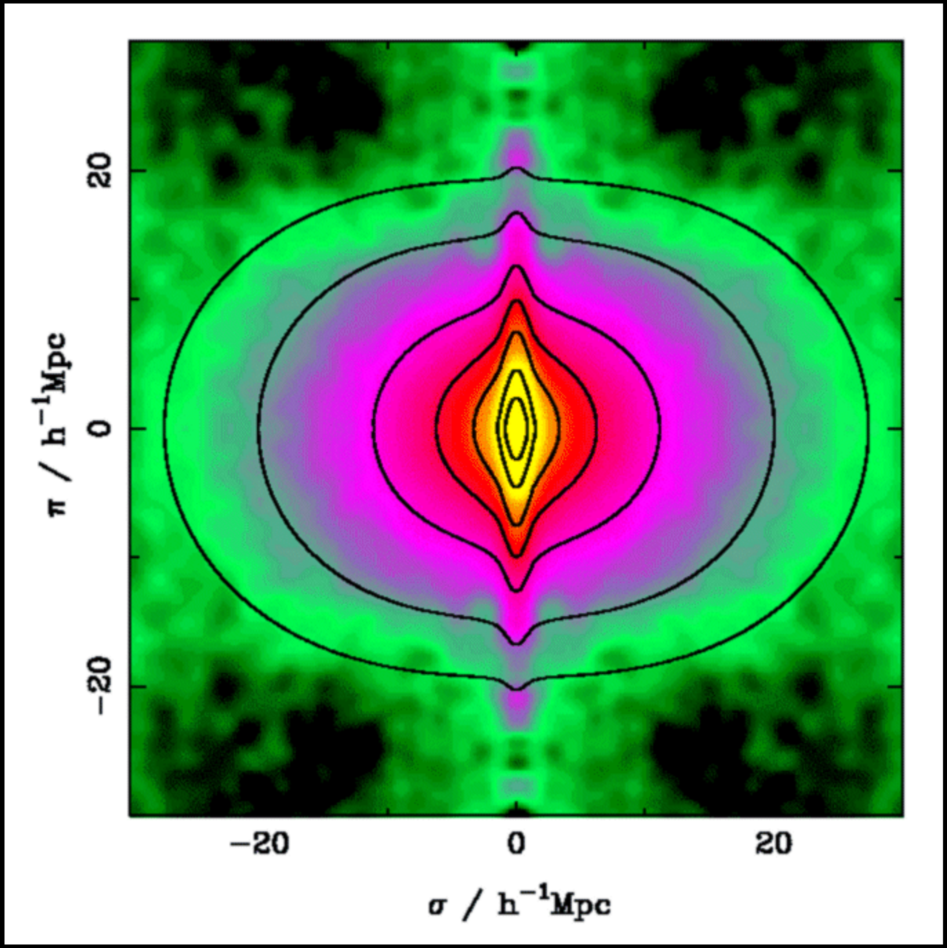
Peculiar velocities

$$P_z = (1 + \beta\mu^2)^2 P_r$$

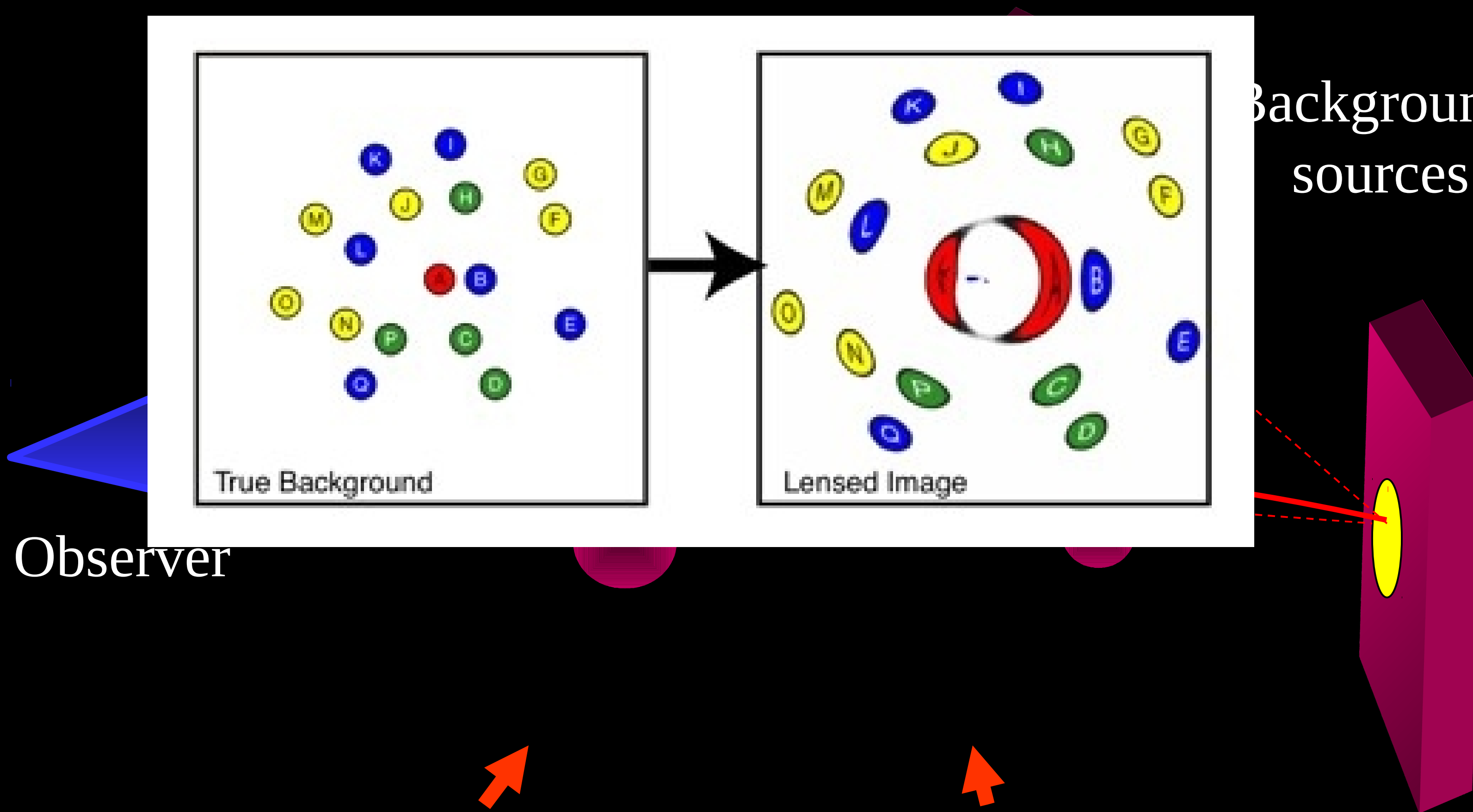
redshift distortion parameter

$$\beta = \frac{\delta'}{\delta b}$$

Kaiser 1987



Weak lensing



Radial distances depend on *geometry* of Universe

Foreground mass distribution depends on *growth/distribution* of structure

The Euclid theorem

5 unknown functions:

Observables:

$$b\delta = \sqrt{P(k_{transv})}$$

$$\beta = \frac{\delta'}{\delta b} = \sqrt{\frac{P(k_{radial})}{P(k_{transv})}} - 1$$

$$P_{ellipt}(k,z) = \int_0^z dz' K(z')(\Phi_k - \Psi_k)^2$$

Conservation equations:

$$\delta' = 3\Phi' - \Box v$$

$$(\Box v)' = -\Box v + \frac{k^2}{Ha}\Psi$$

$$\theta \Box \Box v$$

We can measure 3 combinations and we have 2 theoretical relations…

Theorem: lensing+galaxy clustering allows to measure all (total matter) perturbation variables at first order without assuming any specific gravity theory

The Euclid theorem

$$b(k,z), \delta(k,z), \theta(k,z), \Psi(k,z), \Phi(k,z)$$

From these we can derive the deviations from Einstein's gravity:

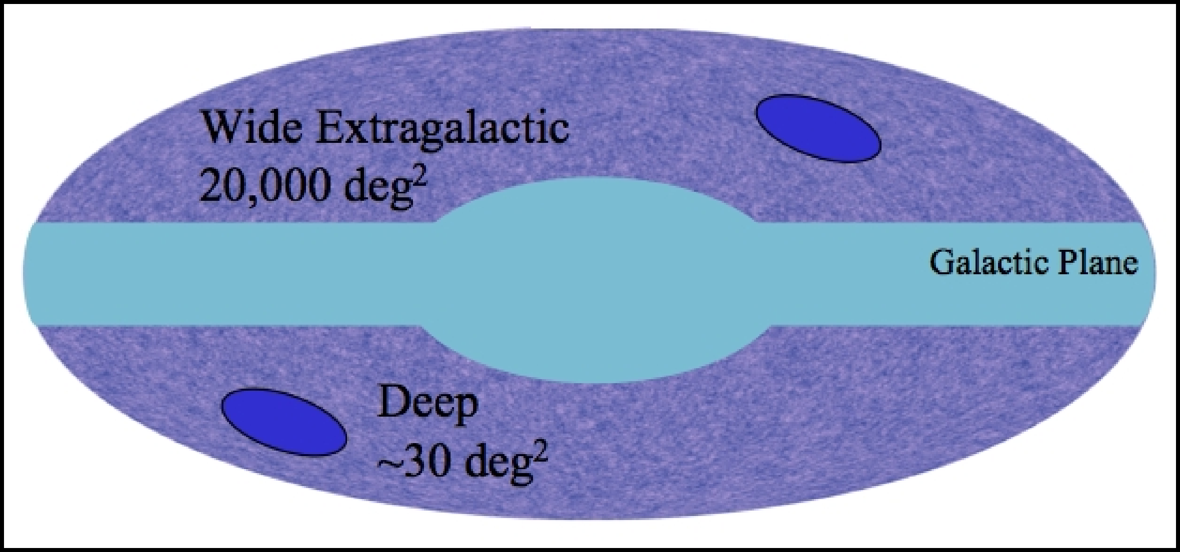
$$Q(k,a) = -\frac{4\pi G a^2 \rho \delta}{k^2 \Psi}$$

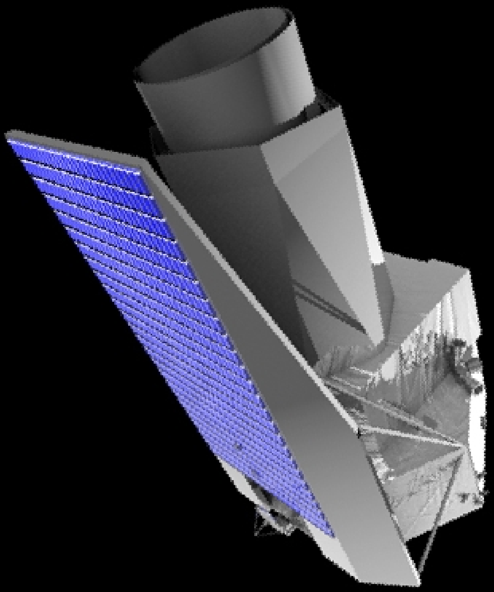
$$\eta(k,a) = \frac{\Phi + \Psi}{\Psi}$$

▪ standard gravity	$Q(k,a)=1$ $\eta(k,a)=0$	
▪ scalar-tensor models	$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{2(F+F'^2)}{2F+3F'^2}$ $\eta(a)=\frac{F'^2}{F+F'^2}$	Boisseau et al. 2000 Acquaviva et al. 2004 Schimd et al. 2004 L.A., Kunz &Sapone 2007
▪ f(R)	$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{1+4m\frac{k^2}{a^2R}}{1+3m\frac{k^2}{a^2R}}, \quad \eta(a)=\frac{m\frac{k^2}{a^2R}}{1+2m\frac{k^2}{a^2R}}$	Bean et al. 2006 Hu et al. 2006 Tsujikawa 2007
▪ DGP	$Q(a)=1-\frac{1}{3\beta}; \quad \beta=1+2Hr_c w_{DE}$ $\eta(a)=\frac{2}{3\beta-1}$	Lue et al. 2004; Koyama et al. 2006
▪ coupled Gauss-Bonnet	$Q(a)=...$ $\eta(a)=...$	see L. A., C. Charmousis, S. Davis 2006

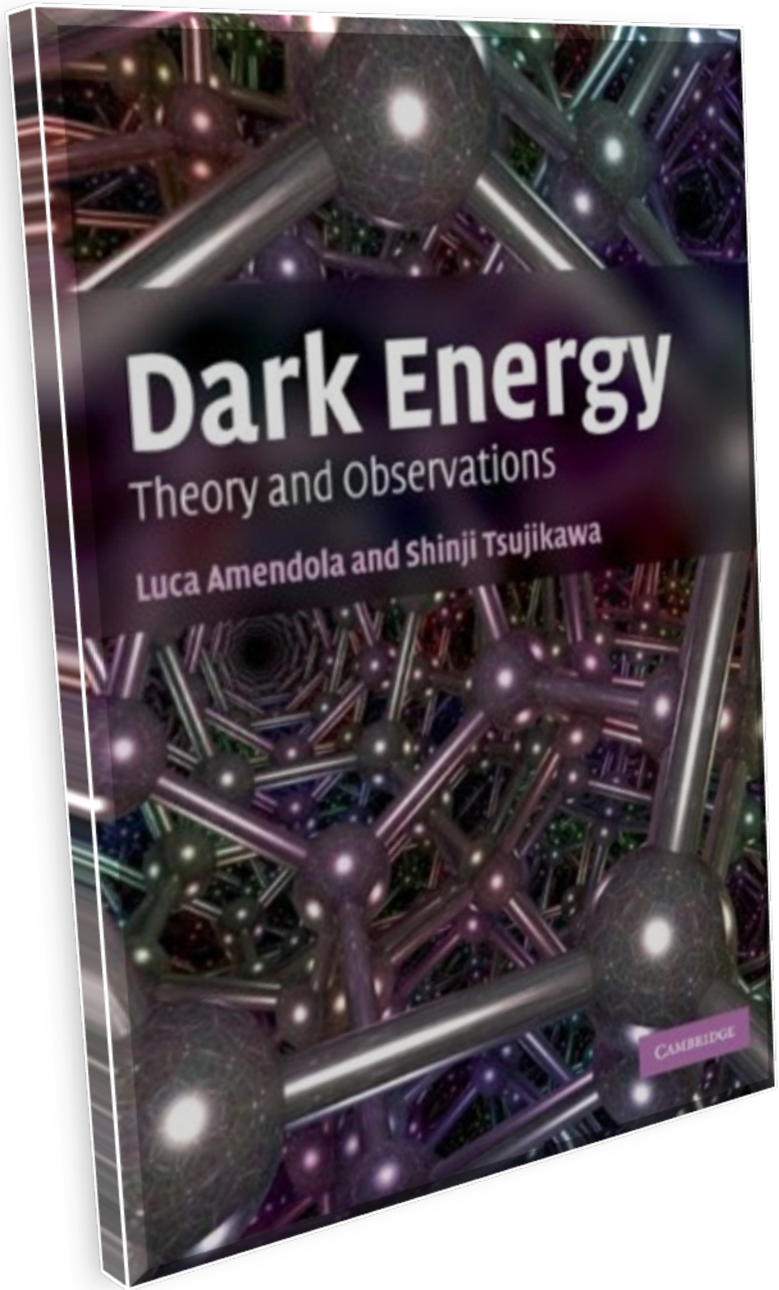
Euclid in a nutshell

- Simultaneous (i) visible imaging (ii) NIR photometry (iii) NIR spectroscopy
- 20,000 square degrees
- 100 million redshifts, 2 billion images
- Median redshift z = 1
- PSF FWHM ~0.18''
- Final ESA selection (launch 2017)
- 500 peoples, 10 countries





Euclid satellite



Cambridge
University
Press

Non-linearity

N-Body simulations

Higher-order perturbation theory

N-body simulations with DE

We assumed:

$$G = G_0(1+\alpha e^{-r/\lambda}) \quad , \lambda \to \infty$$

However matter moves under the action of two potentials,
Newton's potential and scalar field:

$$\Psi, \varphi$$

$$\begin{aligned} \delta' &= -(w+1)\theta - 3(1+w)\Phi' - (1-3w)(C\varphi' + C_{,\phi}\phi'\varphi) + 3(w - c_s^2)\delta(1 - 3C\phi'), \\ \theta' &= -\frac{\theta}{2}[1 - 6w + 3w_t + \frac{w'}{1+w} + C(3w-1)\dot{\phi}] + \frac{c_s^2\delta}{\lambda^2(w+1)} + \frac{1}{\lambda^2}[\frac{C(3w-1)}{w+1}\varphi + \Psi] \end{aligned}$$

N-body simulations with DE

$$\Psi, \varphi$$

$$\Psi = -\frac{3}{2}\lambda^2 \sum_i \Omega_i \delta_i \; .$$

$$\varphi'' + (2 + \frac{\mathcal{H}'}{\mathcal{H}})\varphi' + \varphi([\lambda + \hat{m}_\phi^2 - 2\phi'^2 - 3\sum(1 - 3w_i)\Omega_i C_{i,\phi}] = 3\sum C_i(1 - 3c_s^2)\Omega_i \delta_i \; ,$$

For simplicity I only show linearized equations...

N-body simulations with DE

$$\varphi'' + (2 + \frac{\mathcal{H}'}{\mathcal{H}})\varphi' + \varphi([\lambda + \hat{m}_\phi^2 - 2\phi'^2 - 3\sum(1 - 3w_i)\Omega_i C_{i,\phi}] = 3\sum C_i(1 - 3c_s^2)\Omega_i\delta_i\,,$$

For small scales this becomes

$$\varphi \approx 3Y(k)\lambda^2 C\Omega_m\delta_m\,, \qquad Y(k) = \frac{k^2}{k^2 + a^2m^2}\,,$$

So the resulting potential on the j-th component is

$$G = G_0[1 + \alpha(\varphi)e^{-r/\lambda(\varphi)}]$$

where φ in general is given by the full
solution of the inhomogeneous Klein-Gordon eq.

...a long way to go

Non-linearity:
Higher order perturbation theory

Linear Newtonian perturbations

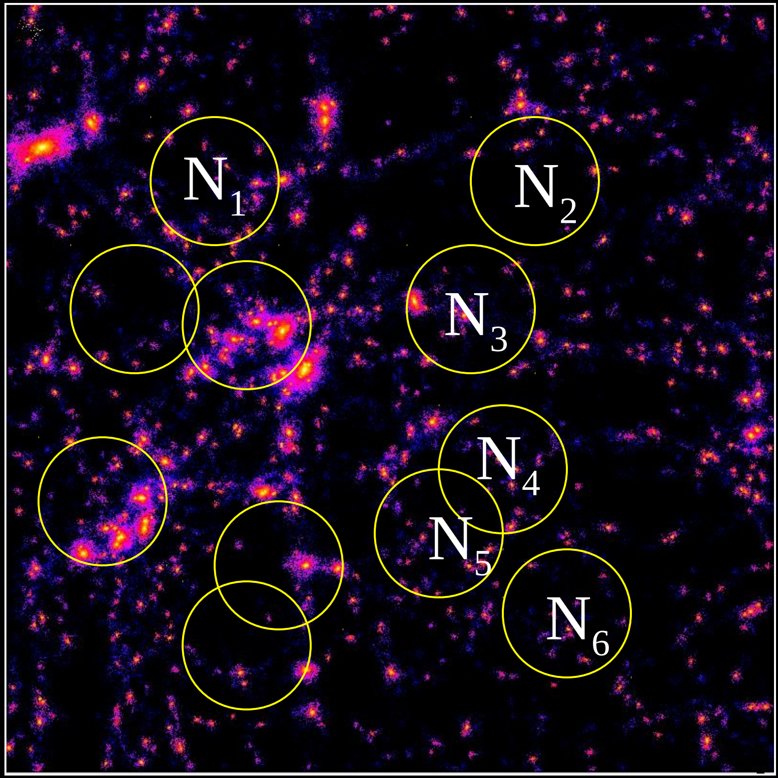
$$\delta' + \vec{\nabla}\bar{v} = 0$$

$$\vec{v}' + (1 + H'/H)\vec{v} = -\frac{3}{2}\Omega\vec{\nabla}\Phi$$

A field initially Gaussian remains Gaussian:
the skewness S_3 is zero

$$S_3 = \frac{<\delta^3>}{<\delta^2>^2} = 0$$

Counts in cells



$$<N> = \bar{N}$$

$$\delta = \frac{N - \bar{N}}{\bar{N}}$$

$$<\delta^2> = \sigma^2$$

$$<\delta^3> = S_3$$

Non-linear Newtonian perturbations

$$\delta' + \vec{\nabla}(1+\delta)\vec{v} = 0$$

$$\vec{v}' + (1 + H'/H)\vec{v} + (\vec{v}\vec{\nabla})\vec{v} = -\frac{3}{2}\Omega\vec{\nabla}\Phi$$

A field initially Gaussian develops a non-Gaussianity:
the skewness S_3 is a constant value

$$S_3 = \frac{<\delta^3>}{<\delta^2>^2} = \frac{34}{7}$$ (Peebles 1981)

Independent of Ω, of eq. of state, etc.: S_3 is a probe of gravitational instability, not of cosmology

Non-linear scalar-Newtonian perturbations

$$\delta' + \vec{\nabla}(1+\delta)\bar{v} = 0$$

$$\text{CDM}: \vec{v}' + (1 + \frac{H'}{H} - \boxed{2\beta\phi})\vec{v} + (\vec{v}\vec{\nabla})\vec{v} = -\frac{3}{2}\Omega(1 + \boxed{\frac{4}{3}\beta^2})\vec{\nabla}\Phi$$

$$\text{Baryons}: \vec{v}' + (1 + \frac{H'}{H})\vec{v} + (\vec{v}\vec{\nabla})\vec{v} = -\frac{3}{2}\Omega\vec{\nabla}\Phi$$

the skewness S_3 is a constant

$$S_3 = \frac{<\delta^3>}{<\delta^2>^2} = \frac{34}{7}(1 + 0.6\beta^2)$$

(L.A. & C. Quercellini, PRL 2004)

therefore S_3 is also a probe of dark energy interaction

Real-time cosmology:
New Observables for Dark Energy

Sandage 1962

$H(z_1)$ $H(z_2)$

VOLUME 136 SEPTEMBER 1962 NUMBER 2

THE CHANGE OF REDSHIFT AND APPARENT LUMINOSITY OF GALAXIES DUE TO THE DECELERATION OF SELECTED EXPANDING UNIVERSES

ALLAN SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
(With an Appendix by G. C. McVITTIE, University of Illinois Observatory, Urbana)

Received February 2, 1962; revised April 13, 1962

ABSTRACT

The redshift and apparent luminosity of any given galaxy are not constant with time for most models of the expanding universe. Redshifts decrease with time because of the braking action of the gravitational field in all exploding models, except for the one where the matter density is zero. Apparent luminosities decrease with time, except for the oscillating model in the contracting phase and for galaxies with very large $\Delta\lambda/\lambda_0$ values, because the distances between galaxies are increasing Redshifts increase with time for every galaxy in the steady-state model.

The theory and numerical results of the deceleration are presented for four selected world models. For a galaxy with redshift $z = \Delta\lambda/\lambda_0 = 0.4$ at the present epoch, the change of redshift with time is found to be $dcz/dt = -11 \times 10^{-6}$ km/sec year for the oscillating model in the expanding phase at $q_0 = +1$; $dcz/dt = -5.9 \times 10^{-6}$ km/sec year for the Euclidean model; $dcz/dt = -4\,3 \times 10^{-6}$ km/sec year for the hyperbolic model at $q_0 = 0\,3516$; and $dcz/dt = +9\,2 \times 10^{-6}$ km/sec year for the steady-state model. These all assume that $H^{-1} = 13 \times 10^9$ years at the present epoch With present optical techniques

$$\Delta v \approx \pm 1 cm/\sec/year$$

IV. CONCLUSION

1. The foregoing considerations show that an "ideal" deceleration test exists between the exploding and the steady-state models in the sense that the *sign* of the effect is reversed. However, for the test to be useful, it would seem that a precision redshift catalogue must be stored away for the order of 10^7 years before an answer can be found because the decelerations are so small by terrestrial standards.

2. For all models, except the oscillating case, it will become more and more difficult to obtain observational information from the universe because the apparent luminosities of galaxies decrease with time. Indeed, if the oscillating case is excluded, there will be a time in the very distant future when most galaxies will recede beyond the limit of easy observation and when data for extragalactic astronomy must be collected from ancient literature.

Loeb 1998

Direct Measurement of Cosmological Parameters from the Cosmic Deceleration of Extragalactic Objects

Abraham Loeb

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

ABSTRACT

The redshift of all cosmological sources drifts by a systematic velocity of order a few m s^{-1} over a century due to the deceleration of the Universe. The specific functional dependence of the predicted velocity shift on the source redshift can be used to verify its cosmic origin, and to measure directly the values of cosmological parameters, such as the density parameters of matter and vacuum, Ω_M and Ω_Λ, and the Hubble constant H_0. For example, an existing spectroscopic technique, which was recently employed in planet searches, is capable of uncovering velocity shifts of this magnitude. The cosmic deceleration signal might be marginally detectable through two observations of $\sim 10^2$ quasars set a decade apart, with the HIRES instrument on the Keck 10 meter telescope. The signal would appear as a global redshift change in the Lyα forest templates imprinted on the quasar spectra by the intergalactic medium. The deceleration amplitude should be isotropic across the sky. Contamination of the cosmic signal by peculiar accelerations or local effects is likely to be negligible.

Subject headings: cosmology: theory

submitted to *ApJ Letters*, Feb. 10th, 1998

Real-time observables

	radial	transverse
global		
local		

Real-time Cosmology

	radial	transverse
global	Expansion rate	anisotropy
local	Gravity at galactic scales: eg Newton vs MOND	

The Sandage effect

$$H_0 \Delta t \approx 10^{-9} \quad (10 yrs)$$

$$10^{-9} c \approx 30 cm/\sec$$

$$1 + z = \frac{a(t_0)}{a(t_s)}$$

$$\Delta z \approx \frac{a(t_0 + \Delta t_0)}{a(t_s + \Delta t_s)} - \frac{a(t_0)}{a(t_s)}$$

$$\Delta z = H_0 \Delta t_0 (1 + z - \frac{H(z)}{H_0})$$

$$\Delta v = \frac{c \Delta z}{1+z} \Big|_{1yr} \approx 1 cm/\sec$$

Redshift evolution as a test of dark energy 9

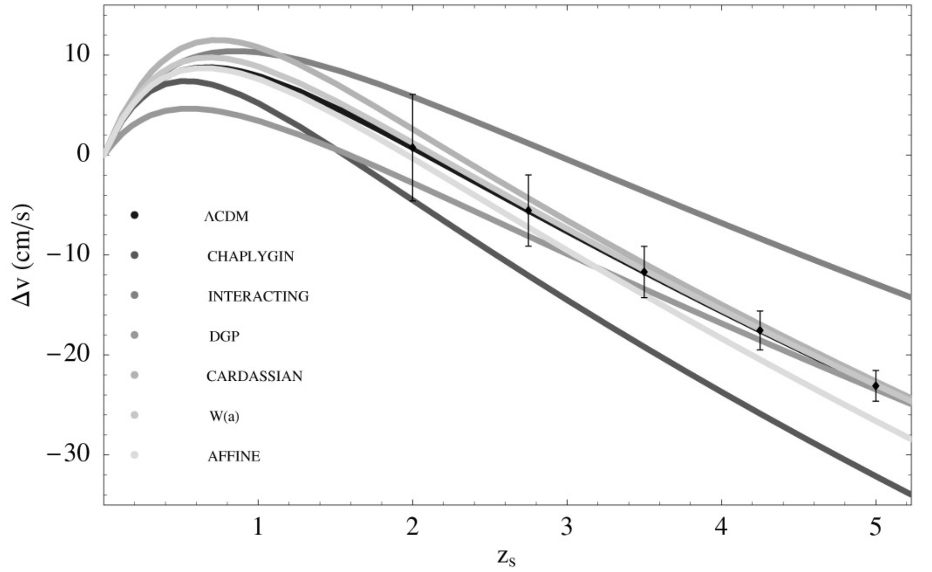
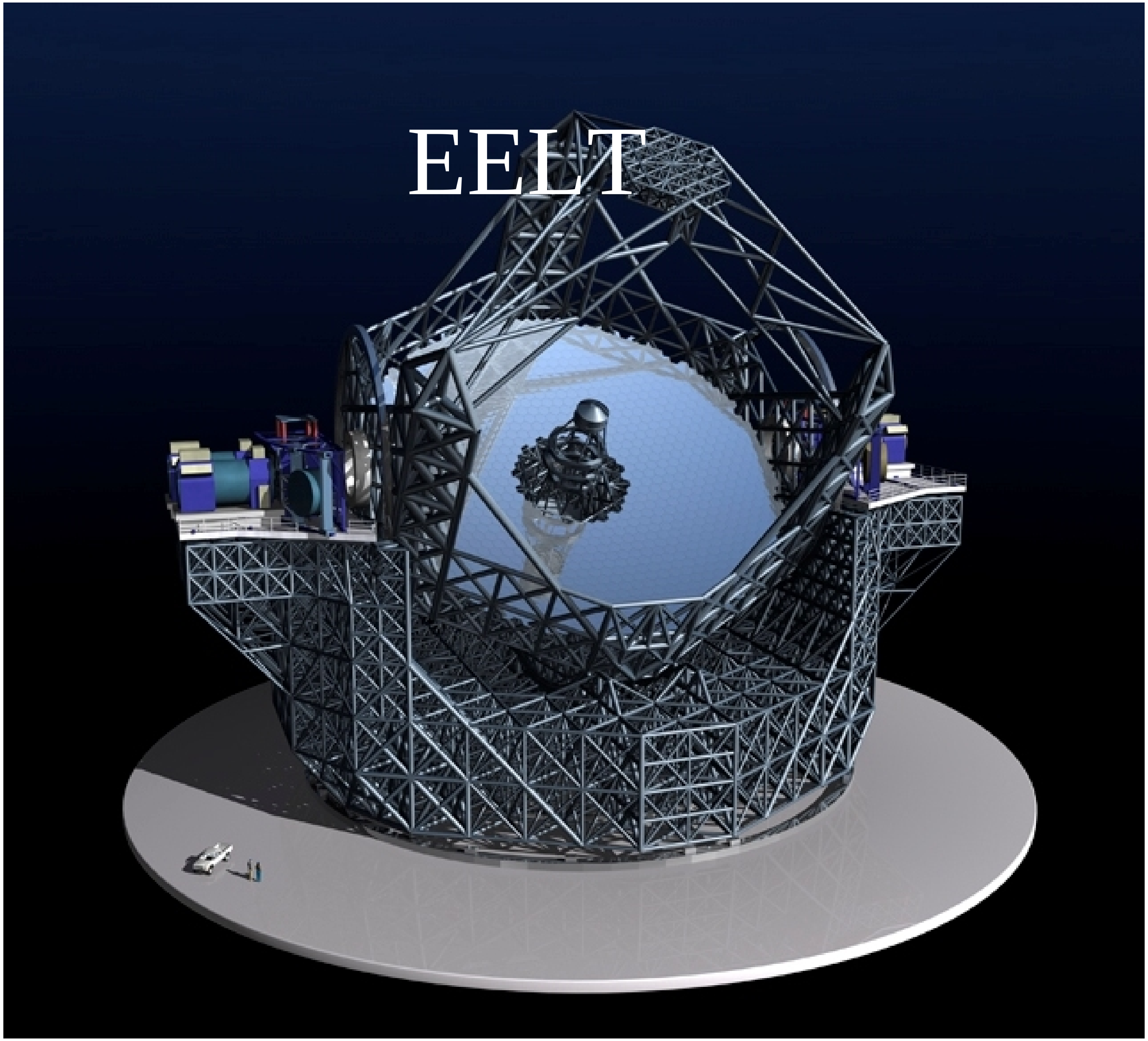
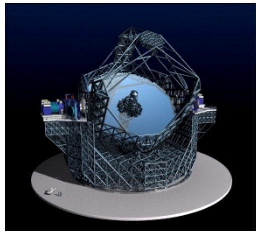


Figure 2. The predicted velocity shift for the models explored in this work, compared to simulated data as expected from the CODEX experiment. The simulated data points and error bars are estimated from Eq. 6, assuming as a fiducial model the standard ΛCDM model. The other curves are obtained assuming, for each non-standard dark energy model, the parameters which best fit current cosmological observations.

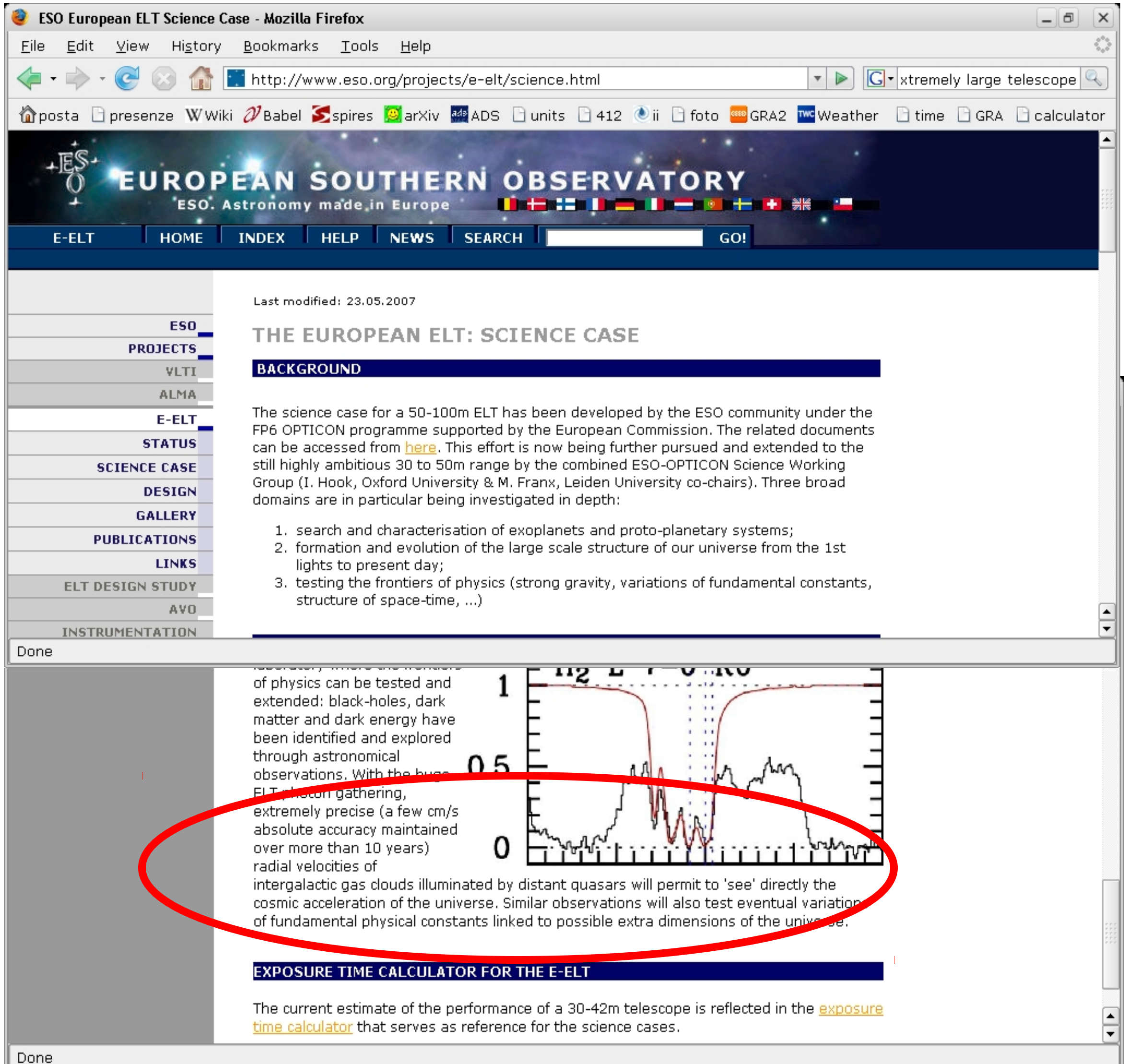
Corasaniti, Huterer, Melchiorri 2007
Balbi & Quercellini 2007

EELT

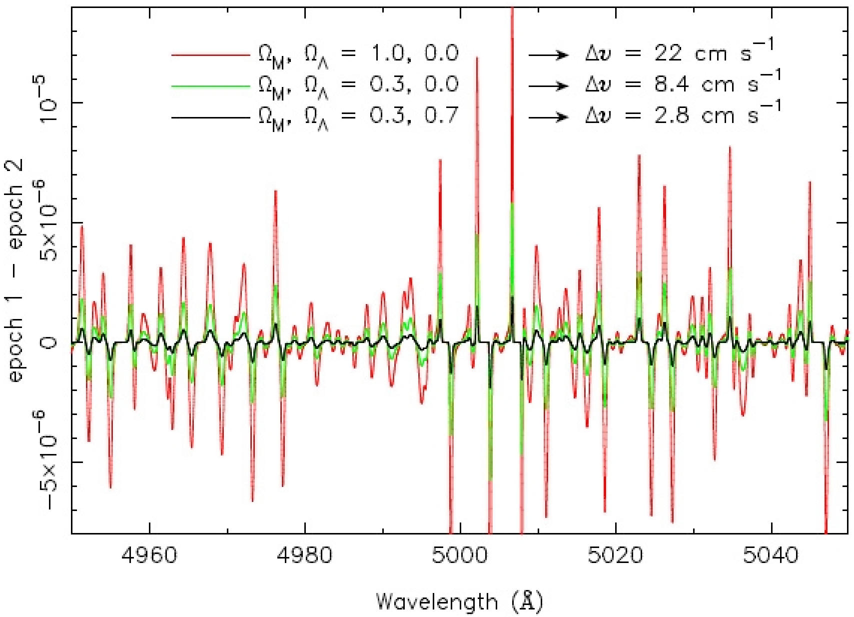




EELT 2007


ESO European ELT Science Case - Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://www.eso.org/projects/e-elt/science.html
xtremely large telescope
posta presenze Wiki Babel spires arXiv ADS units 412 ii foto GRA2 Weather time GRA calculator
EUROPEAN SOUTHERN OBSERVATORY
ESO. Astronomy made in Europe
E-ELT HOME INDEX HELP NEWS SEARCH GO!
ESO
PROJECTS
VLTI
ALMA
E-ELT
STATUS
SCIENCE CASE
DESIGN
GALLERY
PUBLICATIONS
LINKS
ELT DESIGN STUDY
AVO
INSTRUMENTATION
Last modified: 23.05.2007
THE EUROPEAN ELT: SCIENCE CASE
BACKGROUND
The science case for a 50-100m ELT has been developed by the ESO community under the FP6 OPTICON programme supported by the European Commission. The related documents can be accessed from here. This effort is now being further pursued and extended to the still highly ambitious 30 to 50m range by the combined ESO-OPTICON Science Working Group (I. Hook, Oxford University & M. Franx, Leiden University co-chairs). Three broad domains are in particular being investigated in depth:
1. search and characterisation of exoplanets and proto-planetary systems;
2. formation and evolution of the large scale structure of our universe from the 1st lights to present day;
3. testing the frontiers of physics (strong gravity, variations of fundamental constants, structure of space-time, ...)
Done
of physics can be tested and extended: black-holes, dark matter and dark energy have been identified and explored through astronomical observations. With the huge ELT photon gathering, extremely precise (a few cm/s absolute accuracy maintained over more than 10 years) radial velocities of intergalactic gas clouds illuminated by distant quasars will permit to 'see' directly the cosmic acceleration of the universe. Similar observations will also test eventual variations of fundamental physical constants linked to possible extra dimensions of the universe.
1
0.5
0
EXPOSURE TIME CALCULATOR FOR THE E-ELT
The current estimate of the performance of a 30-42m telescope is reflected in the exposure time calculator that serves as reference for the science cases.
Done

CODEX at EELT



This amount is extremely small, and brought Sandage (1962) to conclude that such a measurement was beyond our capabilities. Why do we think that this experiment is possible now? For three reasons: (1) Extremely Large Telescopes such as OWL should be capable of providing the huge number of photons required. (2) In the last two decades our capability of accurately measuring wavelength shifts of astronomical sources has dramatically improved (Mayor et al. 2002). (3) A suitable class of astronomical objects for this measurement has been identified: the Lyα forest lines, which are extremely numerous and beautifully trace the cosmic expansion with negligible peculiar motions (at least ten times smaller than the Hubble flow).

Liske et al. 2008

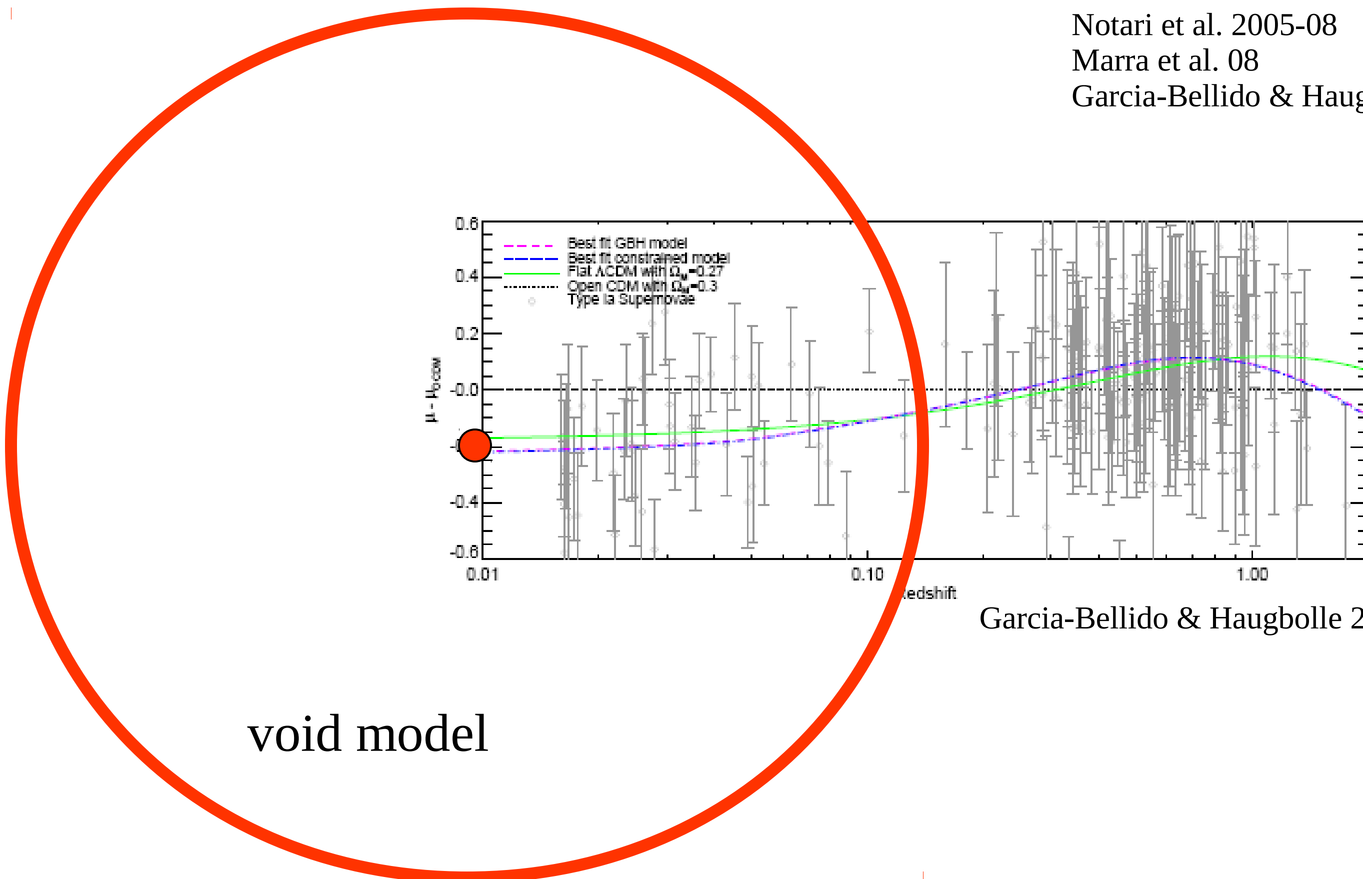
$$\sigma = 2\left(\frac{2350}{S/N}\right)\left(\frac{30}{N_{QSO}}\right)^{1/2}\left(\frac{5}{1+z}\right)^{1.8} cm/s$$

Cosmic Parallax

	radial	transverse
global	Sandage effect	Cosmic parallax
local	Peculiar acceleration	Proper acceleration

Cosmic Parallax

Celerier 2001
Alnes & Amarzguioi 2006,07
Bassett et al. 07
Clifton et al. 08
Notari et al. 2005-08
Marra et al. 08
Garcia-Bellido & Haugbolle 2008



Garcia-Bellido & Haugbolle 2008

Lemaître-Tolman-Bondi models

$$R' \equiv \frac{\partial R}{\partial r}$$

- LTB metrics describe void models

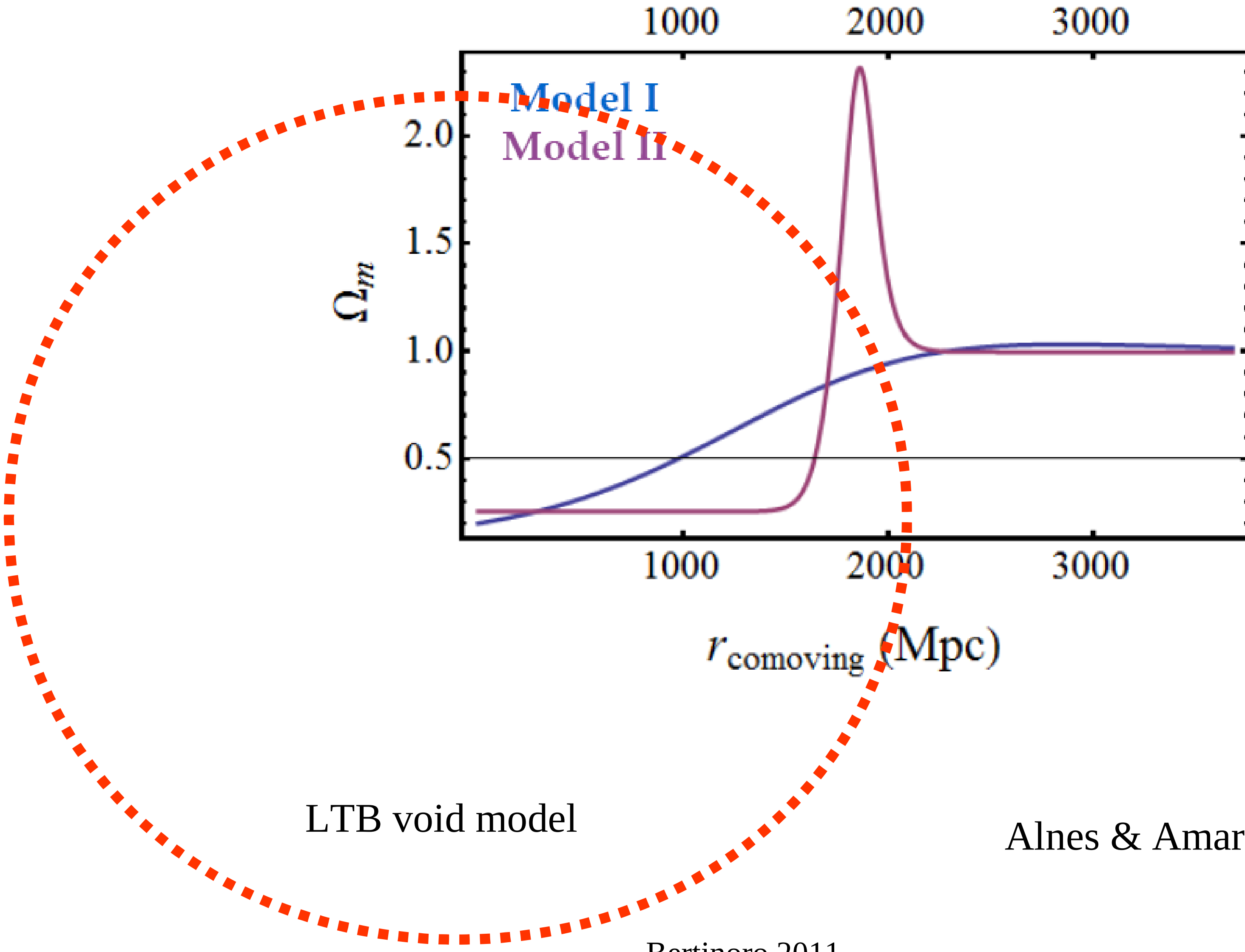
$$ds^2 = -dt^2 + \frac{[R'(t,r)]^2}{1+\beta(r)} dr^2 + R^2(t,r) d\Omega^2$$

- Exact solution in a matter-dominated era

$$R = (\cosh\eta - 1)\frac{\alpha}{2\beta} + R_{\rm lss}\left[\cosh\eta + \sqrt{\frac{\alpha+\beta R_{\rm lss}}{\beta R_{\rm lss}}}\sinh\eta\right]$$

$$\sqrt{\beta}t = (\sinh\eta - \eta)\frac{\alpha}{2\beta} + R_{\rm lss}\left[\sinh\eta + \sqrt{\frac{\alpha+\beta R_{\rm lss}}{\beta R_{\rm lss}}}(\cosh\eta - 1)\right]$$

LTB models



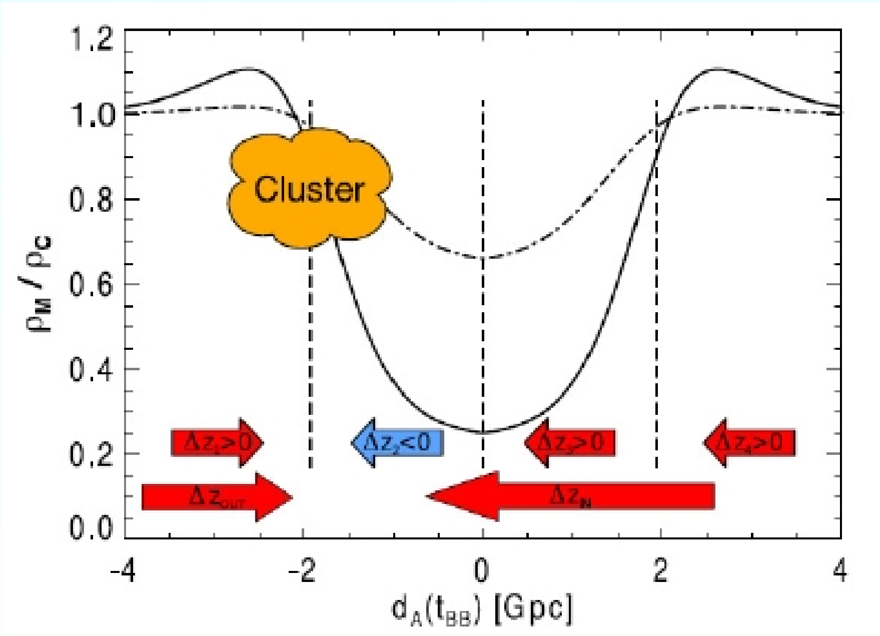
LTB void model

Alnes & Amarzguioi 2006

Constraints on Void Models

- Large voids (> 1.5 Gpc) are in conflict with
  - CMB blackbody spectrum
    - *Caldwell & Stebbins: 0711.3459 (PRL)*
  - Kinematic Sunyaev-Zeldovich effect from large clusters
    - *García-Bellido & Haugbolle: 0807.1326 (JCAP)*

- Sharp transitions could be in conflict with SDSS LRG or SNe distribution (no excess at $z \approx .3$)

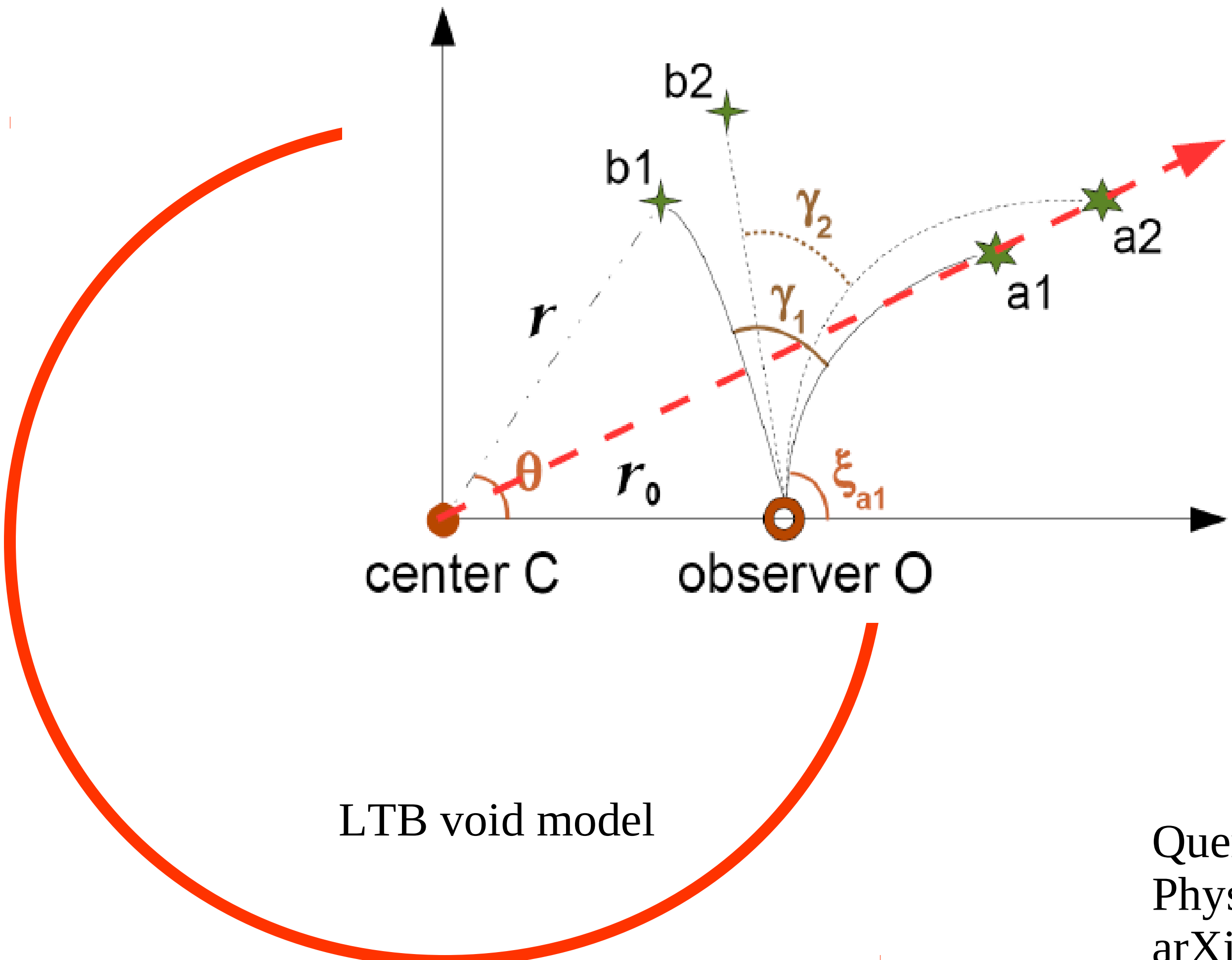


Evolution

Ptolemaic system, I century

LTB void model, XXI century

Cosmic Parallax



$$H_0 \Delta t \approx 10^{-9}$$

$$10^{-9} \, rad \approx 200 \mu as$$

astrometric satellites
GAIA, SIM, Jasmine etc:
1-100 μas

Quercellini, Quartin & LA,
Phys. Rev. Lett. 2009
arXiv 0809.3675

Estimating the Cosmic Parallax

- Calculating the Cosmic Parallax require solving the full LTB geodesic equations
- Simple, *non-consistent* estimate → flat FRW universe with H(t) → H(t, r)
- Assume 2 sources initially separated by ΔX & $\Delta\theta$.

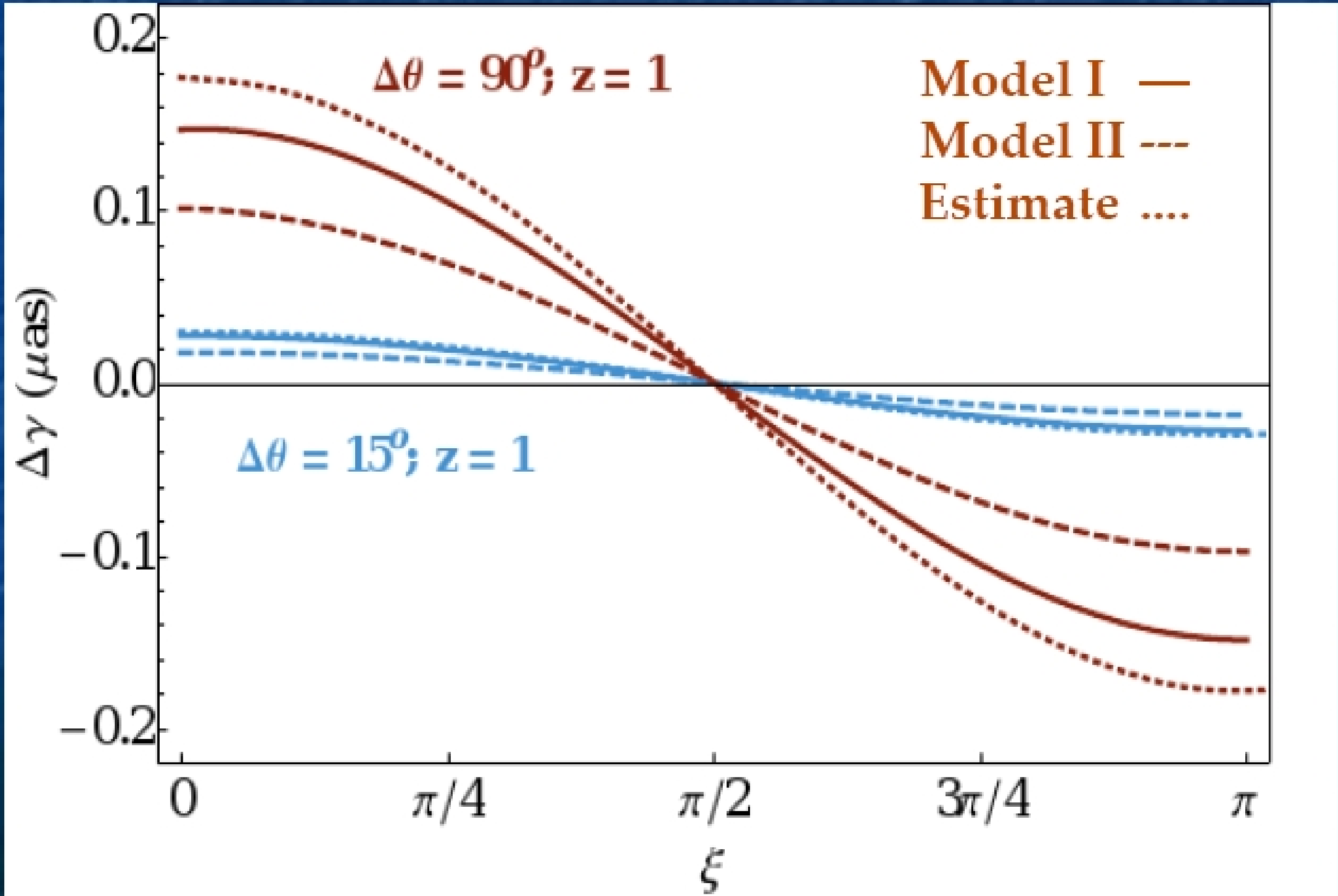
$$\Delta_t \gamma \simeq \Delta t \left(\overline{H}_{\rm obs} - \overline{H}_X\right) \frac{X_{\rm 0bs}}{X}\left(\cos\theta\,\Delta\theta + \sin\theta\,\frac{\Delta X}{X}\right)$$

distance to the void center

“physical” distance

Results

- Actual effect → need to solve the LTB geodesic eqs.
- $\Delta_t\gamma$ in 10 yrs for a pair of quasars at z=1 (typical for Gaia)



Gaia: Complete, Faint, Accurate

	Hipparcos	Gaia
Magnitude limit	12	20 mag
Completeness	7.3 – 9.0	20 mag
Bright limit	0	6 mag
Number of objects	120 000	26 million to V = 15
		250 million to V = 18
		1000 million to V = 20
Effective distance	1 kpc	50 kpc
Quasars	None	5×10^5
Galaxies	None	$10^6 – 10^7$
Accuracy	1 milliarcsec	7 μarcsec at V = 10
		10-25 μarcsec at V = 15
		300 μarcsec at V = 20
Photometry	2-colour (B and V)	Low-res. spectra to V = 20
Radial velocity	None	15 km/s to V = 16-17
Observing	Pre-selected	Complete and unbiased

Cosmic Parallax with Gaia

- SNe → off-center distance $X_0 \leq 150$ Mpc.
- CMB dipole → off-center dist. $X_0 \leq 15$ Mpc.

Alnes & Armazguioui
astro-ph/0607334
astro-ph/0610331

- Assuming:
  - $X_0 = 15$ Mpc (aggressive);
  - Astrometric precision of 30 μas;
  - Nominal Gaia duration ($\Delta t = 5$ years)
- Gaia can detect the Cosmic Parallax at 1σ if

  # sources ≥ 450,000 (conservative)

Noise and Sistematics

- Most obvious source of noise → peculiar velocities

$$\Delta_t \gamma_{\rm pec} = \left(\frac{v_{\rm pec}}{500\,\frac{\rm km}{\rm s}}\right)\left(\frac{D_A}{1\,{\rm Gpc}}\right)^{-1}\left(\frac{\Delta t}{10\,{\rm years}}\right)\mu as$$

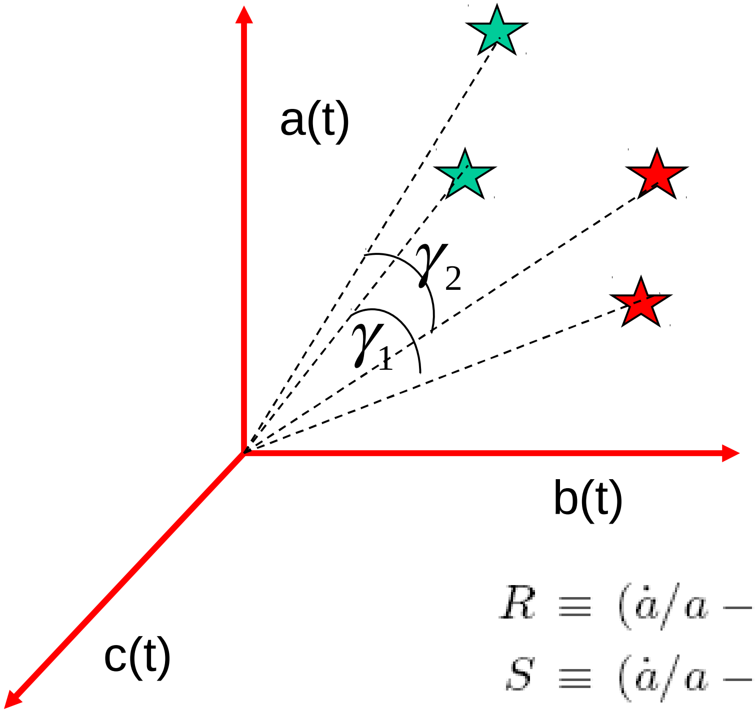
- Most serious source of noise → changing aberration due to acceleration of the solar system

Gaia predicts ≈ 4 μas effect, of which 90% could be subtracted → 0.4 μas spurious dipole

Kovalevsky 2003

Not only LTB

Bianchi I



$$R \equiv (\dot{a}/a - \dot{b}/b)/H = \Sigma_x - \Sigma_y \,,$$
$$S \equiv (\dot{a}/a - \dot{c}/c)/H = 2\Sigma_x - \Sigma_y \,.$$

Current limits from CMB

$$R = \frac{\Delta H}{H} \leq 10^{-4}$$ at z = 1000

$$\frac{\Delta H}{H} \leq 10^{-8}$$ at z = 0 in a ΛCDM universe

$$\frac{\Delta H}{H} \leq ?$$ at z = 0 in anisotropic dark energy

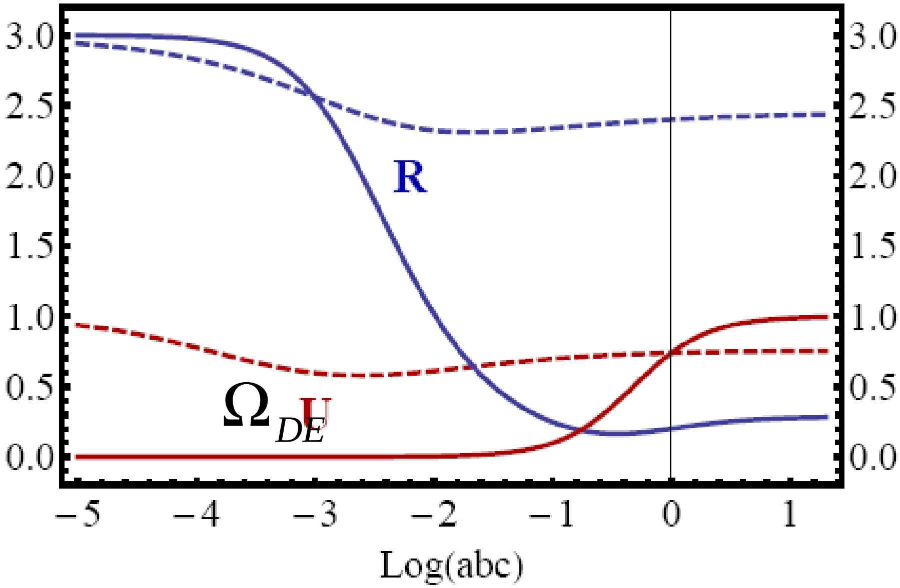
Anisotropic dark energy

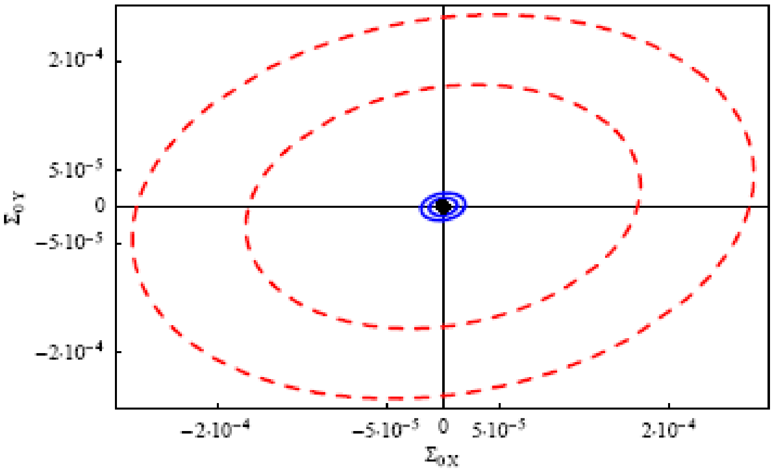
Mota & Koivisto 2008

$$T^{\mu}_{(\mathrm{DE})\nu} = \mathrm{diag}(-1, w, w+3\delta, w+3\gamma)\rho_{\mathrm{DE}},$$

$$R \equiv (\dot{a}/a - \dot{b}/b)/H = \Sigma_x - \Sigma_y\,,$$
$$S \equiv (\dot{a}/a - \dot{c}/c)/H = 2\Sigma_x - \Sigma_y\,.$$

Experiment	N_s	σ_{acc}	Δt
Gaia	500,000	10μas	5yrs
Gaia+	1,000,000	1μas	10yrs



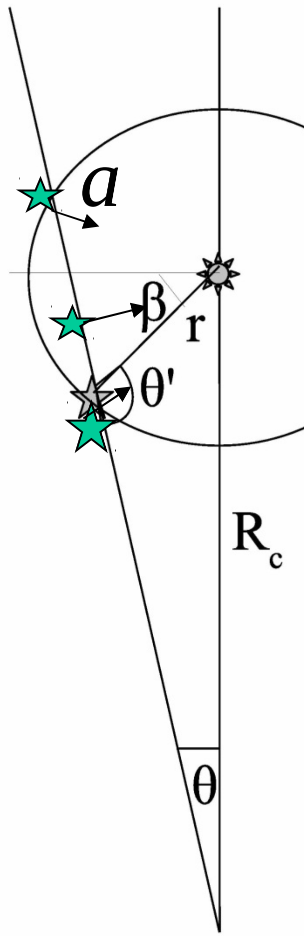


$$R = \frac{\Delta H}{H} \leq 10^{-4} \quad , \textit{ at any } z$$

Peculiar Acceleration

	radial	transverse
global	Sandage effect	Cosmic parallax
local	Peculiar acceleration	Proper acceleration

Peculiar Acceleration



$$a_{pec} = \sin\beta \frac{GM(r)}{r^2}$$

The PA is a direct probe of the gravitational potential: it
does not assume virialization or hydrostatic equilibrium.

Peculiar Acceleration

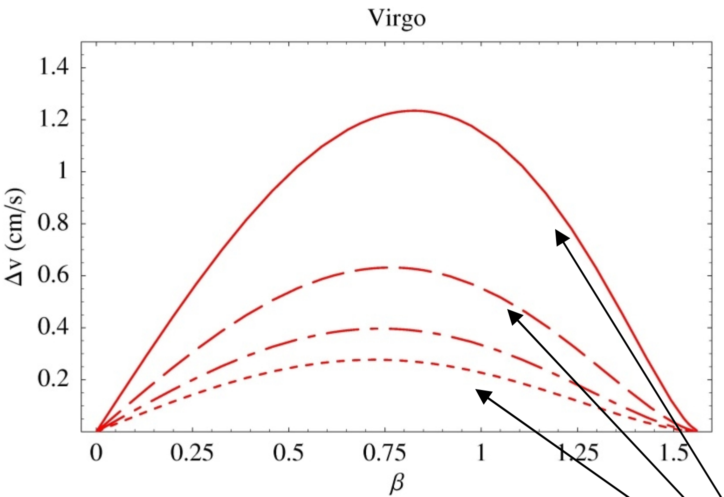
$$\rho_{NFW}(r) = \frac{\delta_c \rho_c}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}, \quad r_s = r_v / c$$

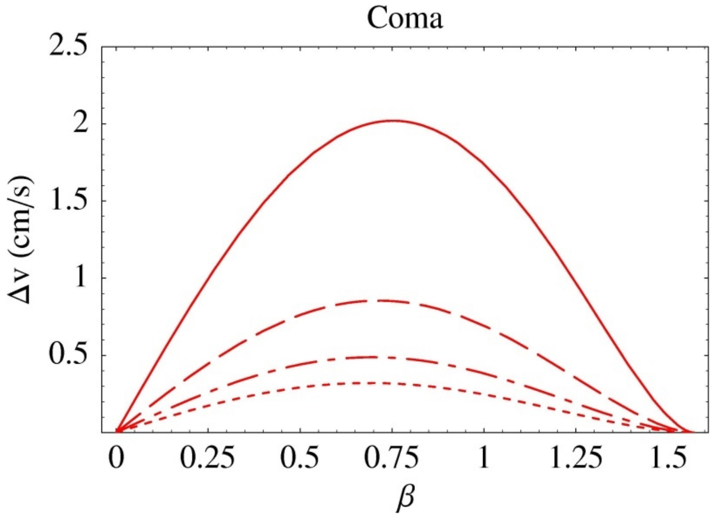
$$s(\beta) = \Delta v = \left(2\frac{cm}{\sec}\right)\sin\beta \frac{\Delta t}{10yr}\frac{M_v}{10^{14}M_\Theta}\left(\frac{r_s}{0.5Mpc}\right)^{-2} C\left(\frac{\log(1+\frac{r}{r_s})}{(r/r_s)^2} - \frac{1}{\frac{r}{r_s}(1+\frac{r}{r_s})}\right)_{r=R_c\theta/\cos\beta}$$

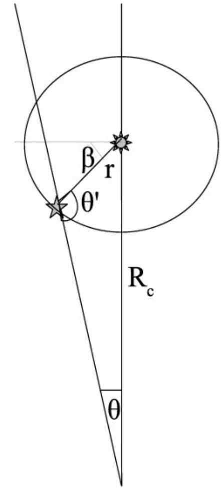
	Mass	r_s
Andromeda	10^{11}	20 kpc
Virgo	1.2×10^{15}	0.55 Mpc
Coma	1.2×10^{15}	0.29 Mpc

Peculiar Acceleration

$$s(\beta)=\Delta v=\left(2\frac{cm}{\sec}\right)\sin\beta\,\frac{\Delta T}{10yr}\,\frac{M_v}{10^{14}M_\Theta}\left(\frac{r_s}{0.5Mpc}\right)^{-2}C\left(\frac{\log(1+\frac{r}{r_s})}{(r/r_s)^2}-\frac{1}{\frac{r}{r_s}(1+\frac{r}{r_s})}\right)$$



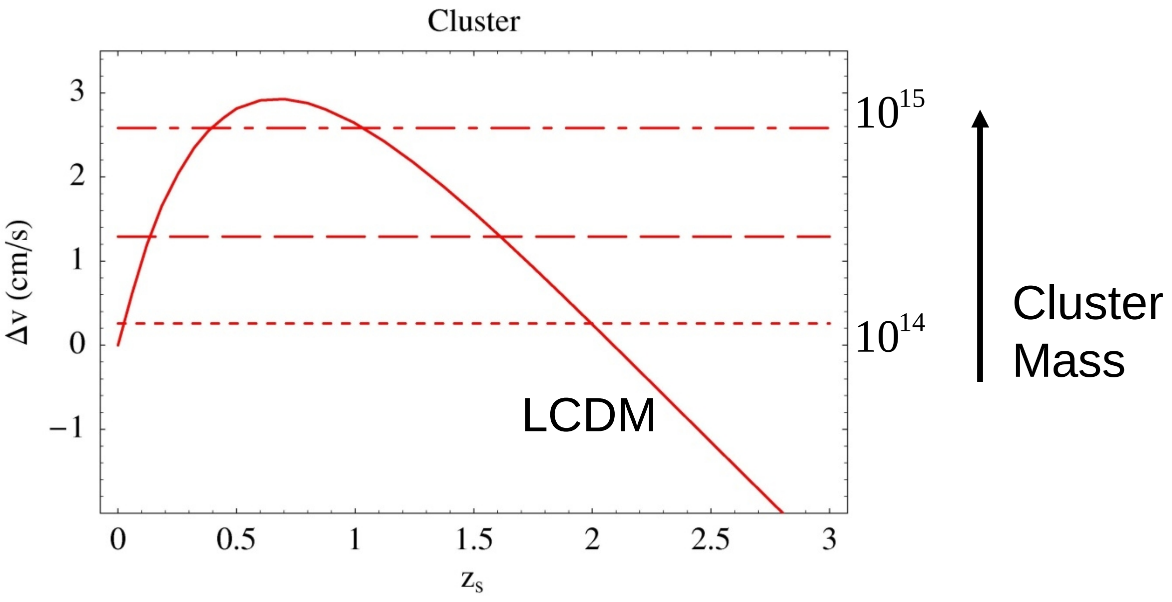




different
lines of sight

L.A., A. Balbi, C. Quercellini,
astro-ph arXiv/0708.1132
Phys.Lett.B660:81,2008

PA versus Sandage effect



Peculiar acceleration in the Galaxy

- Can we use the peculiar acceleration to discriminate among **competing gravity theories**?
- Steps:
  - model the galaxy as a disc+CDM halo and derive the peculiar acceleration signal
  - model the galaxy as a disc in modified gravity (MOND)
  - analyse the different morphology of the signal in the Milky way

Spiral galaxy: Newton

test particle outside the disc, where the presence/absence of a CDM halo is more influent.

- Disc: Kuzmin potential

$$\phi_K = -\frac{MG}{\left[R^2 + (|z|+h)^2\right]^{1/2}} \qquad a_K = -\frac{MG}{\left[R^2 + (|z|+h)^2\right]}$$

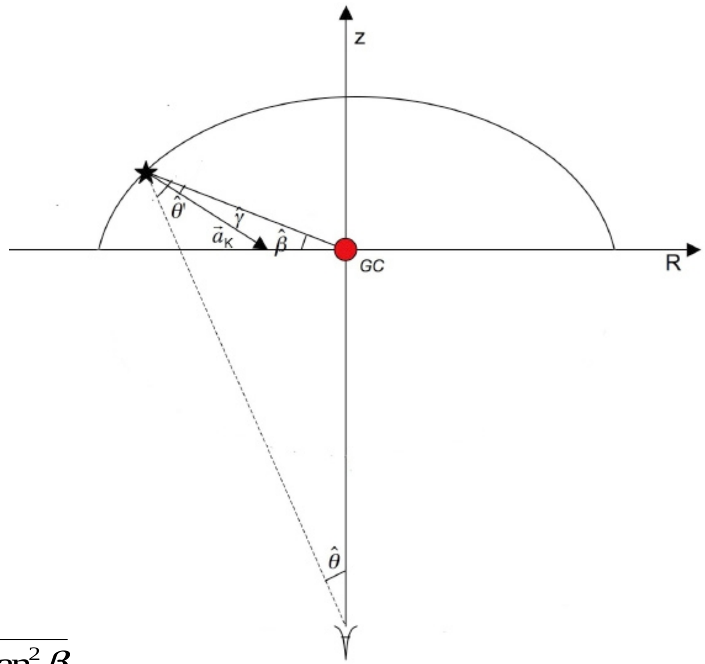
- CDM halo: logarithmic

$$\phi_L = \frac{1}{2} v_o^2 \log\left(R_c^2 + R^2 + \frac{z^2}{q^2}\right)$$

- The total line of sight acceleration:

$$a_{s,K} = \frac{MG}{R_g^2\theta^2\left[1+\left(|\tan\beta| + \frac{h}{R_g\theta}\right)^2\right]} \sin(\beta \mp \gamma)$$

$$a_{s,L} = \frac{v_0^2 R_g \theta \sqrt{1+\frac{\tan^2\beta}{q^2}}}{R_c^2 + R_g^2\theta^2\left(1+\frac{\tan^2\beta}{q^2}\right)} \sin\beta$$



C. Quercellini, L.A., A. Balbi 2008
arXiv:0807.3237

$$\Delta v = (a_{s,K} + a_{s,L})\Delta t$$

Spiral galaxy: MOND

- Beckenstein-Milgrom modified Poisson equation

$$\nabla\cdot\left[\mu\left(\frac{|\nabla\psi|}{a_0}\right)\nabla\psi\right]=4\pi G\rho$$

- For configurations with spherical, cylindrical or plane symmetry

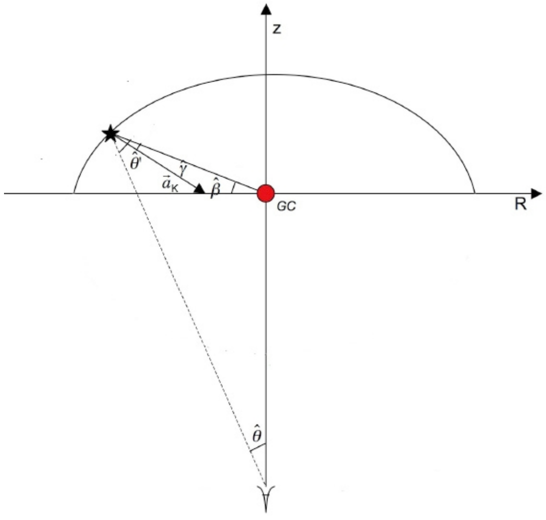
$$\mu(x)=\frac{x}{\sqrt{1+x^2}} \qquad \left[\mu\left(\frac{|\nabla\psi|}{a_0}\right)\nabla\psi\right]=\nabla\phi_N \qquad a_M=\nabla\psi$$

- Assuming $a_M = a_K \frac{\left(1+\sqrt{1+\frac{4a_0^2}{|a_K|^2}}\right)^{1/2}}{\sqrt{2}}$ and solving for

Spiral galaxy: MOND

- peculiar acceleration in MOND:

$$a_{s,M} = \frac{\left(MG \left(1 + \sqrt{1 + \frac{4a_0^2}{M^2G^2} R_g^4 \theta^4 \left[1 + \left(|\tan\beta| + \frac{h}{R_g \theta} \right)^2 \right]^2 } \right) \right)^{1/2}}{\sqrt{2} R_g^2 \theta^2 \left[1 + \left(|\tan\beta| + \frac{h}{R_g \theta} \right) \right]} \cdot \sin(\beta \mp \gamma)$$



Most accelerated globular clusters

TABLE III: The ten globular clusters having the highest difference in signal between the CDM halo configuration and MOND. Astronomical data are from [12]

Name	v (cm/s)[a]	RA (hours)[b]	dec (degrees)	l (degrees)	b (degrees)	R_{Sun} (kpc)	R_{gc} (kpc)[c]	x (kpc)	y (kpc)	z (kpc)
Pal 1	1.18	03 33 23.0	+79 34 50	130.07	19.03	10.9	17.0	-6.6	7.9	3.6
NGC 2298	1.18	06 48 59.2	-36 00 19	245.63	-16.01	10.7	15.7	-4.3	-9.4	-3.0
NGC 1851	1.17	05 14 06.3	-40 02 50	244.51	-35.04	12.1	16.7	-4.3	-8.9	-6.9
NGC 1904 (M 79)	1.16	05 24 10.6	-24 31 27	227.23	-29.35	12.9	18.8	-7.6	-8.3	-6.3
NGC 288	1.15	00 52 47.5	-26 35 24	152.28	-89.38	8.8	12.0	-0.1	0.0	-8.8
NGC 5272 (M 3)	1.13	13 42 11.2	+28 22 32	42.21	78.71	10.4	12.2	1.5	1.4	10.2
NGC 5904 (M 5)	1.11	15 18 33.8	+02 04 58	3.86	46.80	7.5	6.2	5.1	0.3	5.4
NGC 1261	1.09	03 12 15.3	-55 13 01	270.54	-52.13	16.4	18.2	0.1	-10.1	-12.9
NGC 362	1.08	01 03 14.3	-70 50 54	301.53	-46.25	8.5	9.4	3.1	-5.0	-6.2
NGC 7099 (M 30)	1.07	21 40 22.0	-23 10 45	27.18	-46.83	8.0	7.1	4.9	2.5	-5.9

$$\Delta v \approx 1.5\, cm/\sec/\, yr$$

Newton vs. MOND

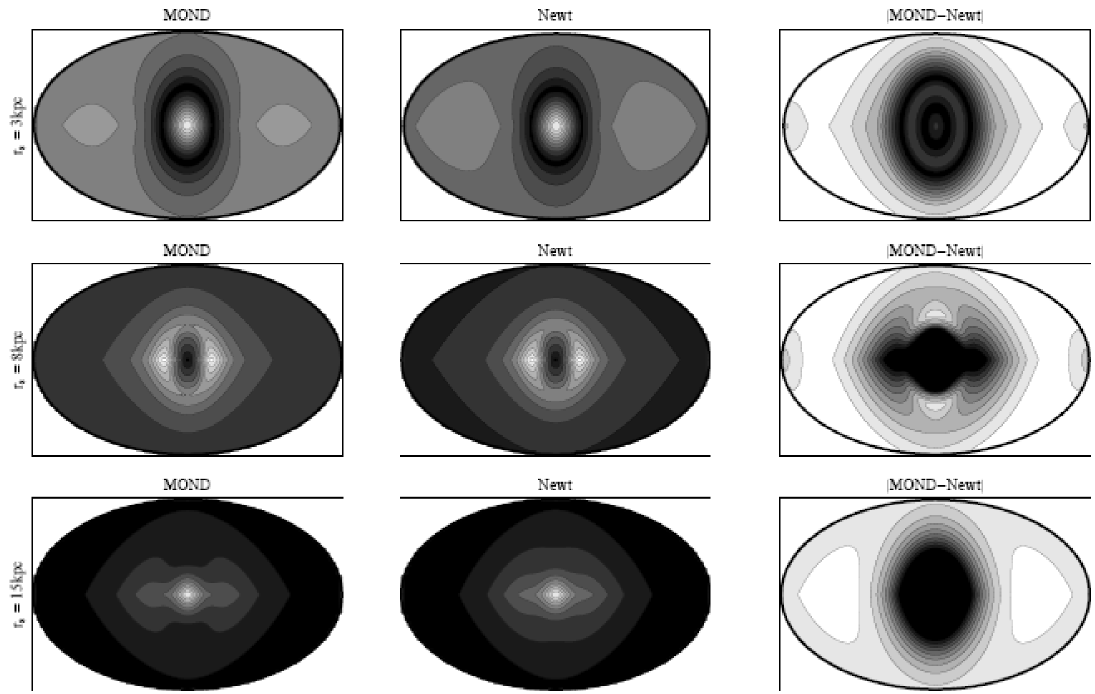
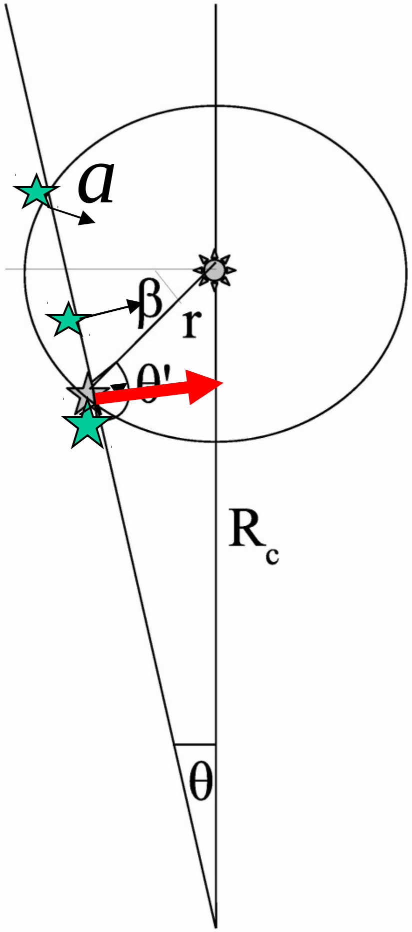


FIG. 10: Comparison in the velocity shift signal (for T=15 years) as seen in the sky from our position in the Milky Way, for the MOND, CDM halo configuration, and their difference (left to right) and for three distances from the Sun (3, 8 and 15 kpc, top to bottom). The sky signal is plotted in galactic coordinates and in Mollweide projection.

Proper Acceleration

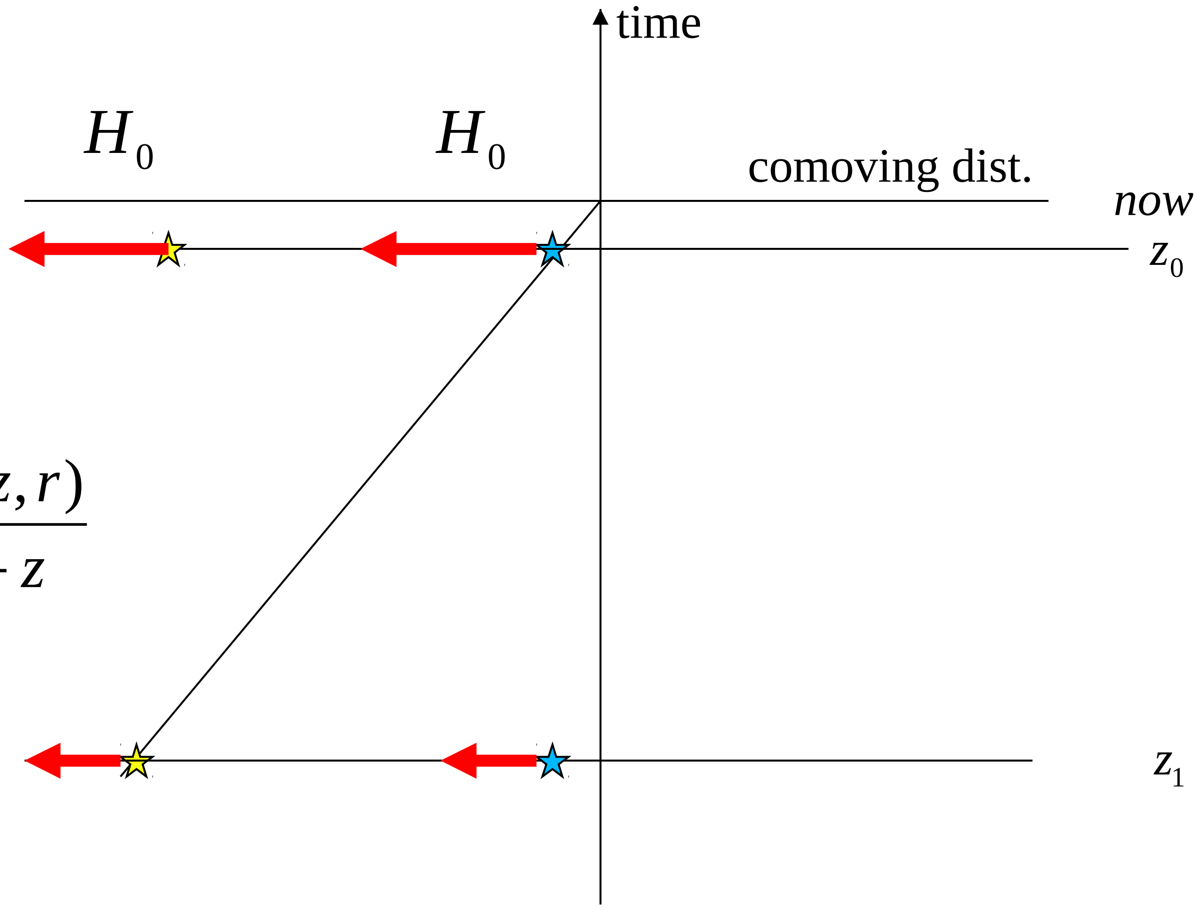


$$a_{pec} = \cos\beta \frac{GM(r)}{r^2}$$

The PropAcc could be seen by averaging over many stars in open and globular clusters

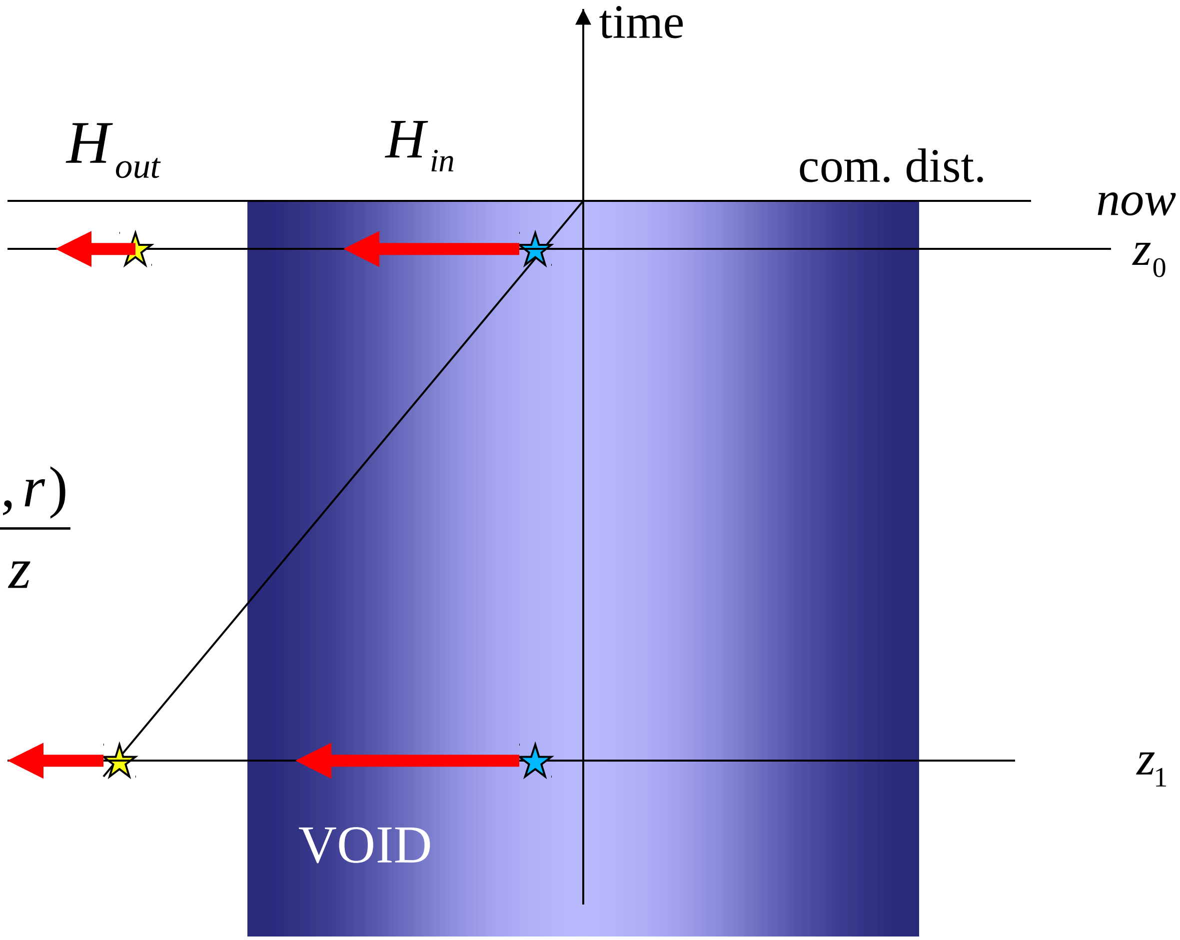
$$\sqrt{N} = 0.83P(\frac{r}{8kpc})(\frac{r_s}{100pc})(\frac{300km/sec}{v})^2(\frac{10y}{\Delta t_s})(\frac{5y}{\Delta t_M}) \cdot \sin\theta'$$

One null cone



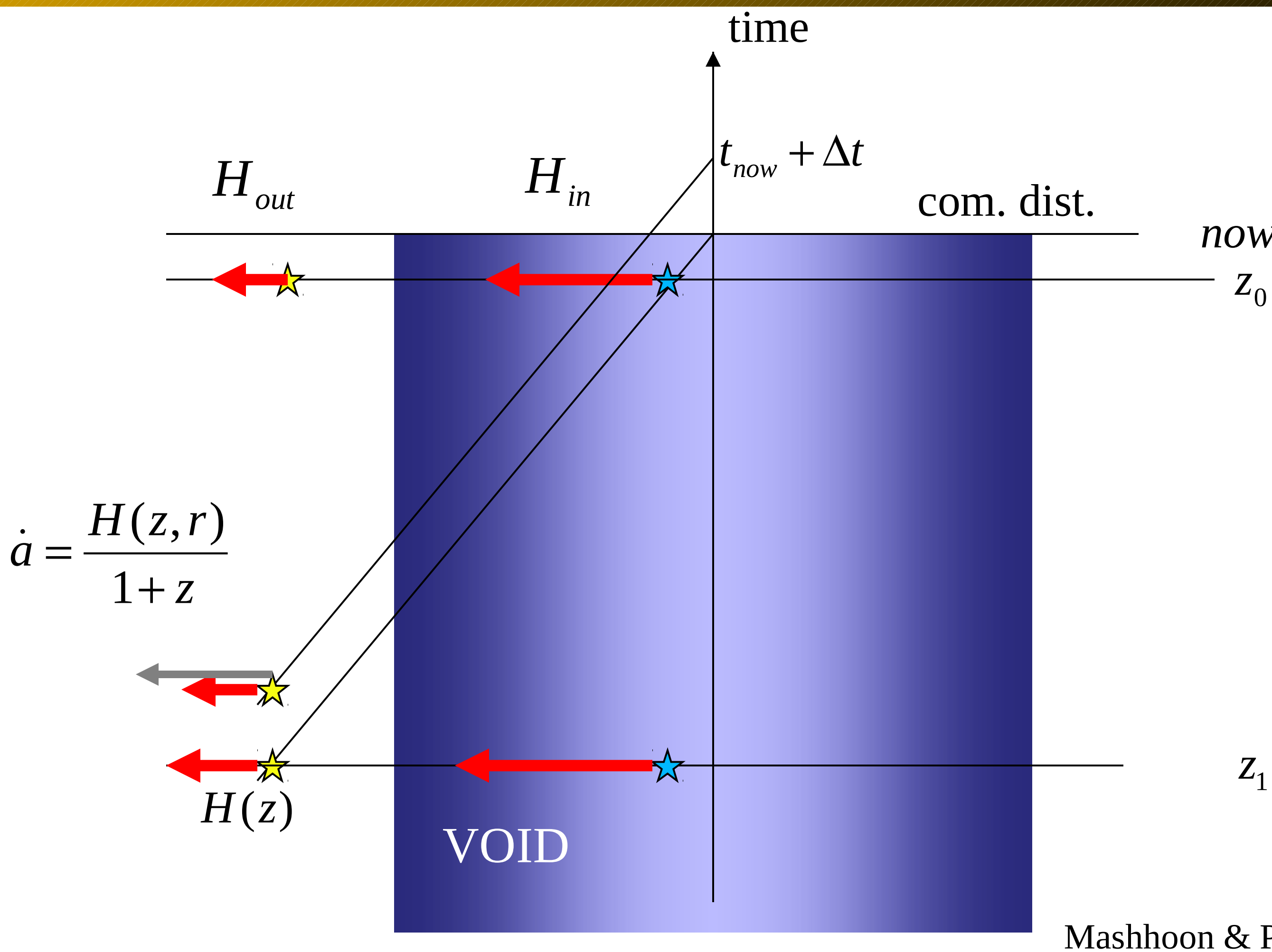
$$\dot{a} = \frac{H(z,r)}{1+z}$$

One null cone



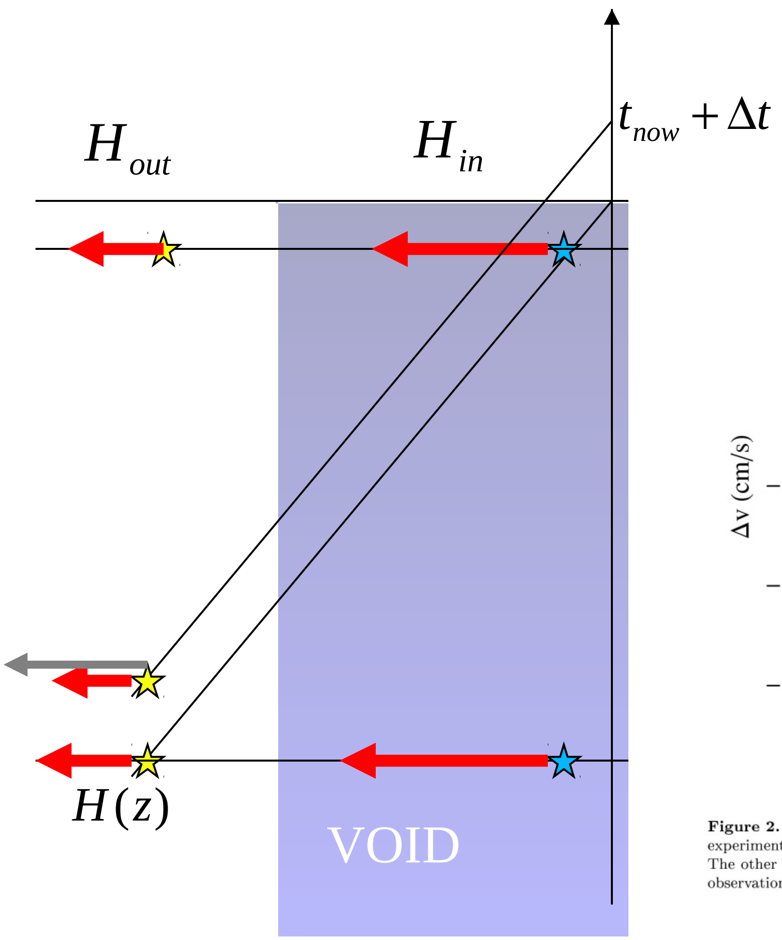
$$\dot{a} = \frac{H(z,r)}{1+z}$$

Two null cones are better than one!



Mashhoon & Partovi 1985
Uzan, Clarkson & Ellis 2007
Quartin, Quercellini, L.A. 2009

Two null cones are better than one!



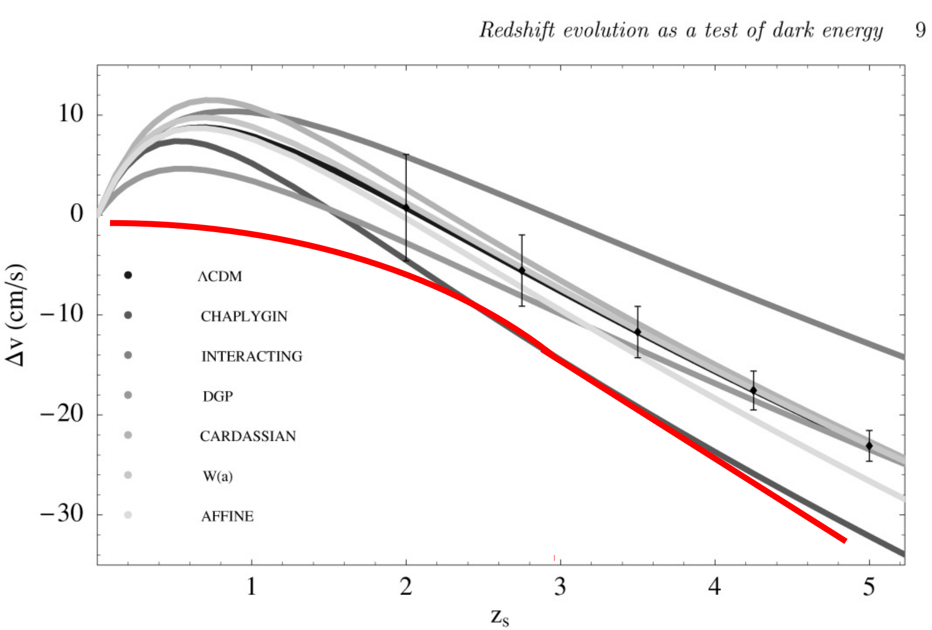
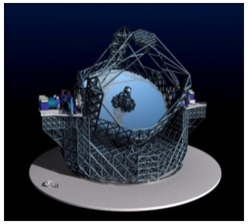


Figure 2. The predicted velocity shift for the models explored in this work, compared to simulated data as expected from the CODEX experiment. The simulated data points and error bars are estimated from Eq. 6, assuming as a fiducial model the standard ΛCDM model. The other curves are obtained assuming, for each non-standard dark energy model, the parameters which best fit current cosmological observations.

Conclusions

Euclid



EELT

- The task of understanding the nature of Dark energy requires a combined use of several observables
- We need to combine weak lensing and clustering to reconstruct the metric at first order
- We need to use real-time observables to distinguish between real and apparent acceleration
- Together with the Cosmic Parallax we can reconstruct the

full 3D picture of cosmic kinematics !

Gaia

Memo for the future

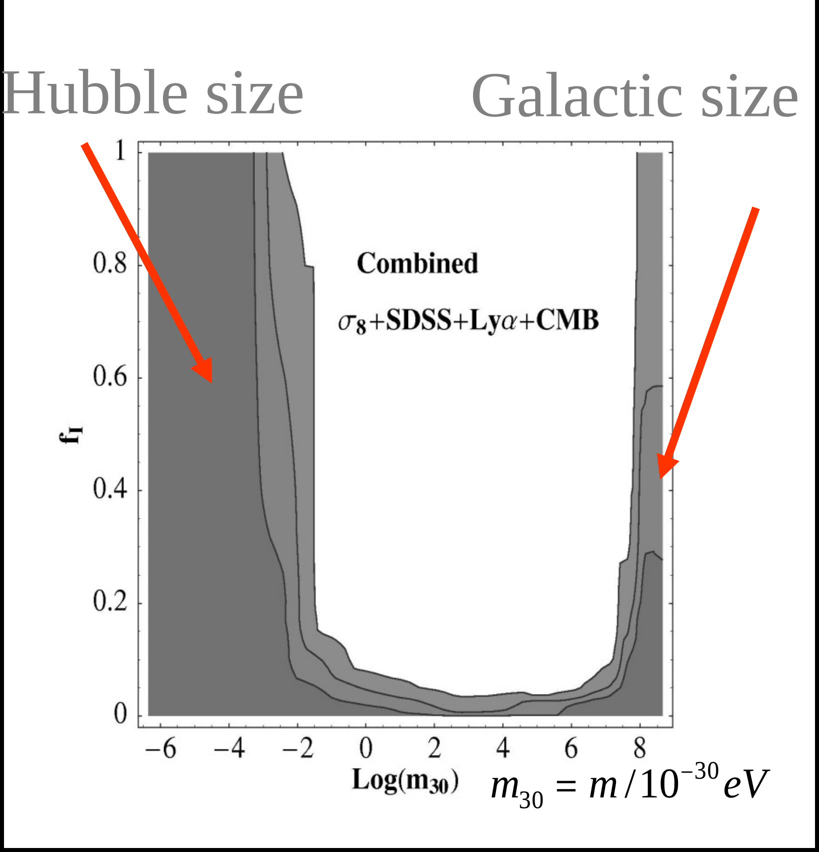
- The Sandage-Loeb effect is a direct measure of the expansion/acceleration of the Universe
- The Cosmic Parallax is a direct test of anisotropy
- The Peculiar/Proper Acceleration is a direct measure of the gravitational potential
- **Full 3D picture of cosmic and local kinematics !**
- A sensitivity of 1 cm/sec could be achieved with the next generation of ELTs
- A sensitivity of 1-10 mu arcsec will be achieved by planned astrometric missions like GAIA, SIM, Jasmine
- New observables for DE, cosmology and gravity theories !

An ultra-light scalar field

$$c_{s,\phi}^2 = \frac{\delta P}{\delta \rho} \simeq \frac{\langle \dot{\phi}\dot{\varphi}\rangle - m_\phi^2 \langle \phi\varphi\rangle}{\langle \dot{\phi}\dot{\varphi}\rangle + m_\phi^2 \langle \phi\varphi\rangle} \simeq \frac{k^2}{4a^2 m_\phi^2} \,.$$

Adopting a PNGB potential

$$f_I = \frac{\Omega_F}{\Omega_{DM}}$$



L.A. & R. Barbieri 2005