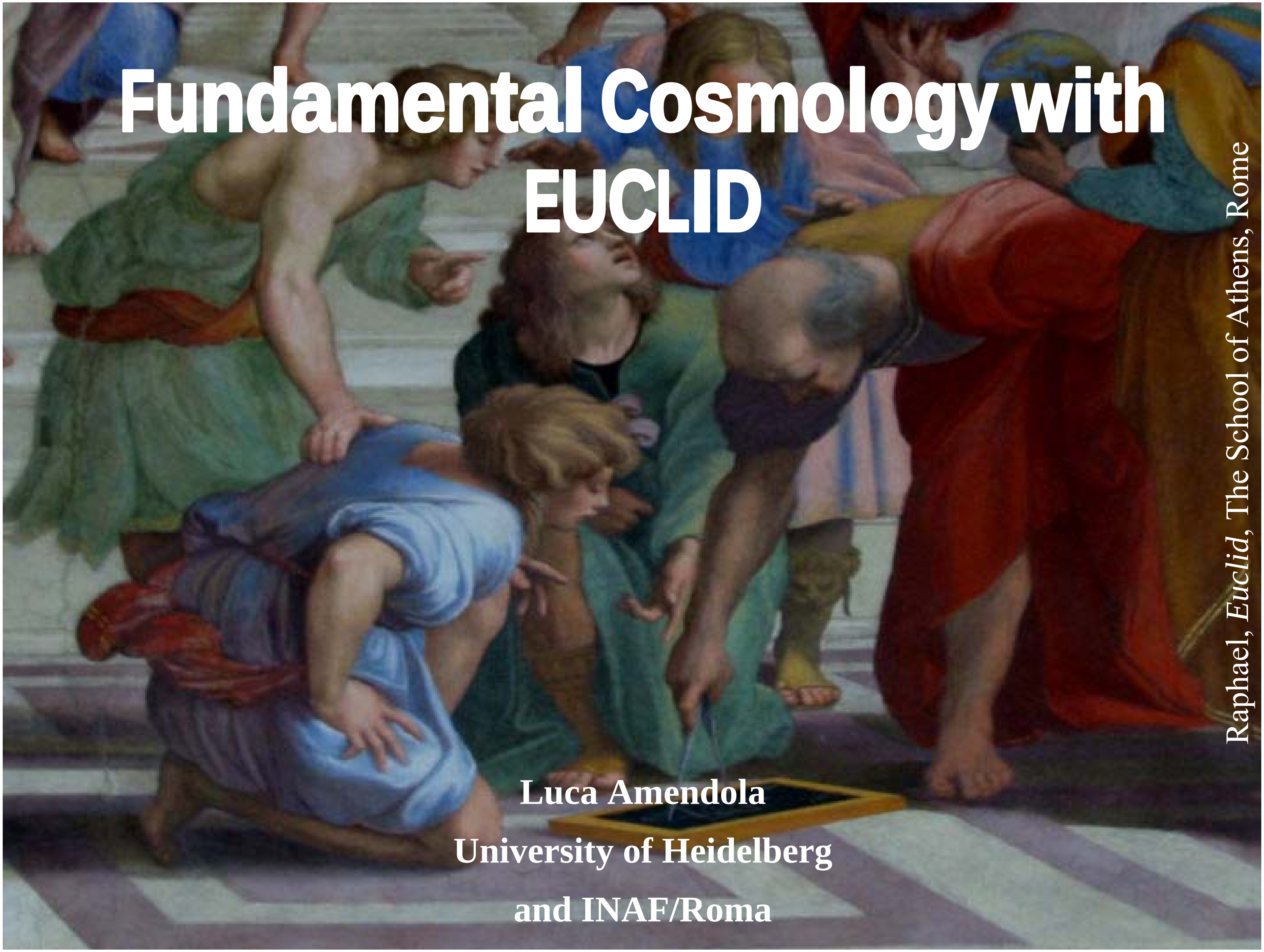
Fundamental Cosmology with EUCLID



Raphael, *Euclid*, The School of Athens, Rome

Luca Amendola

University of Heidelberg

and INAF/Roma

The reconstruction of space-time geometry with Euclid

Dark matter and inflation with Euclid

Synergy of Euclid with Plank, LHC, Gaia, EELT

Cosmic degeneracy

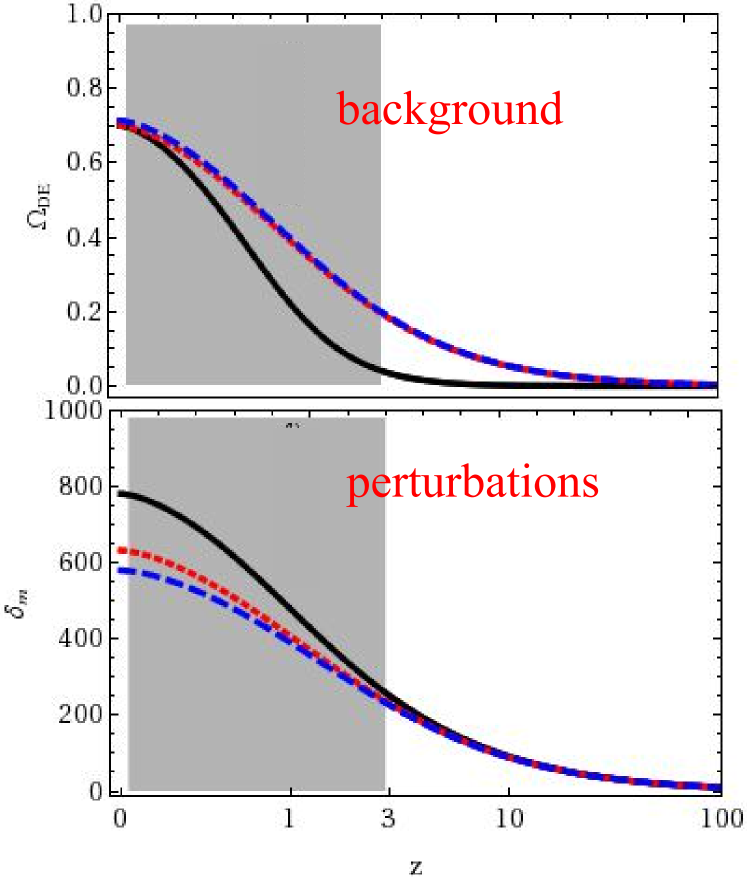
The background expansion only probes

$$H(z)$$

The matter clustering growth probes

$$\delta(k,z)$$

$$\delta''+(1+\frac{H'}{H})\delta-\frac{3}{2}\Omega_m\delta \neq 0$$



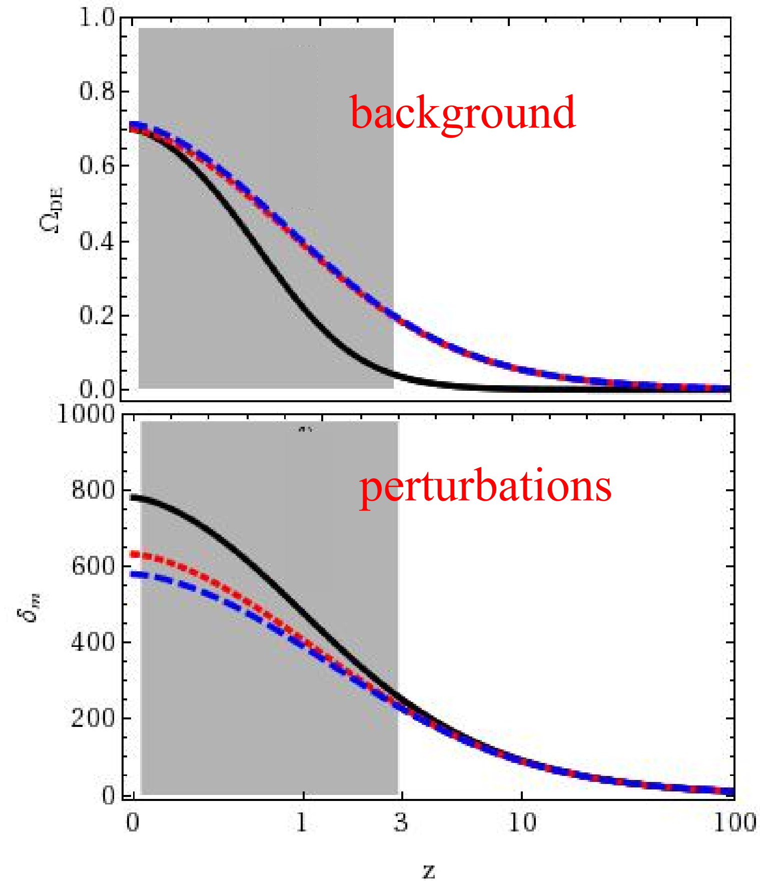
What background hides perturbations reveal

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

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

At the linear perturbation level and sub-horizon scales

- modified Poisson's equation $$k^2\Psi = -4\pi G a^2 Q(k,a)\rho_m \delta_m$$

- non-zero anisotropic stress $$\eta(k,a) = \frac{\Phi + \Psi}{\Psi}$$

Modified Gravity at the linear level

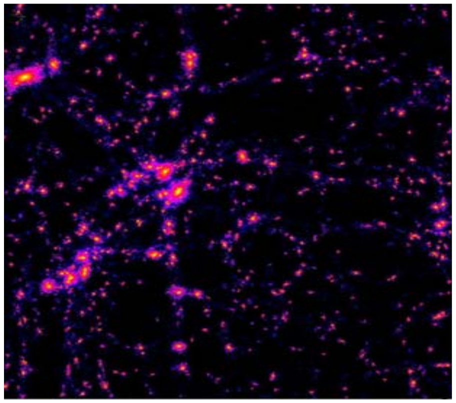
▪ standard gravity	$Q(k,a)=1$ $\eta(k,a)=0$	
▪ scalar-tensor models	$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{2(F+F'^2)}{2F+3F'^2}$ $\eta(a)=\frac{F'^2}{F+F'^2}$	Boisseau et al. 2000 Acquaviva et al. 2004 Schimd et al. 2004 L.A., Kunz &Sapone 2007
▪ f(R)	$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{1+4m\frac{k^2}{a^2R}}{1+3m\frac{k^2}{a^2R}}, \quad \eta(a)=\frac{m\frac{k^2}{a^2R}}{1+2m\frac{k^2}{a^2R}}$	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	$Q(a)=...$ $\eta(a)=...$	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

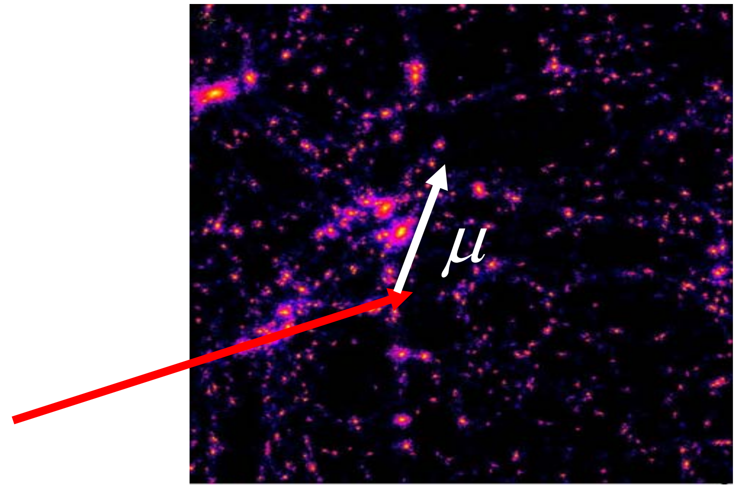
$$\delta'' + (1 + \frac{H'}{H})\delta = \frac{k^2}{a^2}\Psi$$



massless particles respond to Φ-Ψ

$$\alpha = \int \nabla_{perp}(\Psi - \Phi)dz$$

Reconstruction of the metric



Correlation of galaxy positions:
galaxy clustering

$$P_{gal}(k,z,\mu) = (1+\beta\mu^2)^2 b^2 \delta^2(k,z)$$

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

Correlation of galaxy ellipticities:
galaxy weak lensing

$$P_{ellipt}(k,z) \propto (\Phi - \Psi)^2$$

The Euclid theorem

Observables:

$$b\delta = \sqrt{P(k,z,transv)}$$

$$\frac{\delta'}{\delta b} = \sqrt{P(k,z,rad)/P(k,z,transv)} - 1$$

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

Conservation equations:

$$\delta' = 3\Phi' - \frac{\theta}{Ha}$$

$$\theta' = -\theta + \frac{k^2}{Ha}\Psi$$

5 unknown variables: $b(k,z), \delta(k,z), \theta(k,z), \Psi(k,z), \Phi(k,z)$

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

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

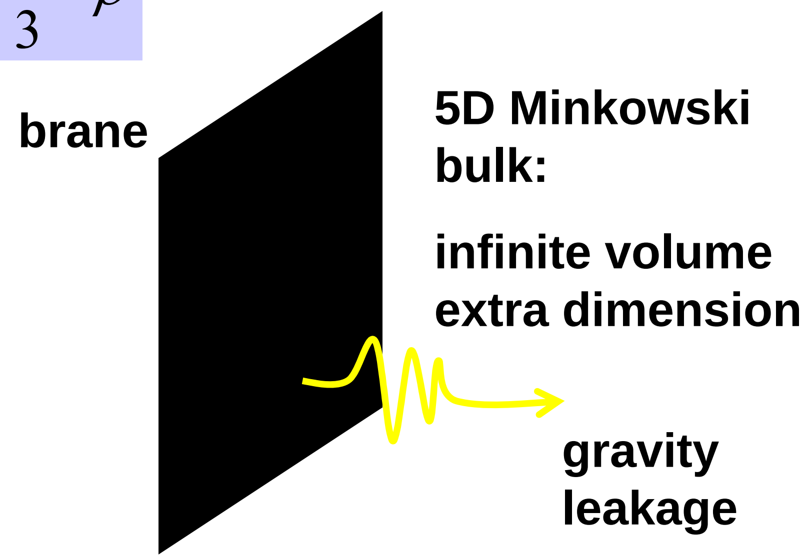
ESTEC 2009

An example: 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:

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

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

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

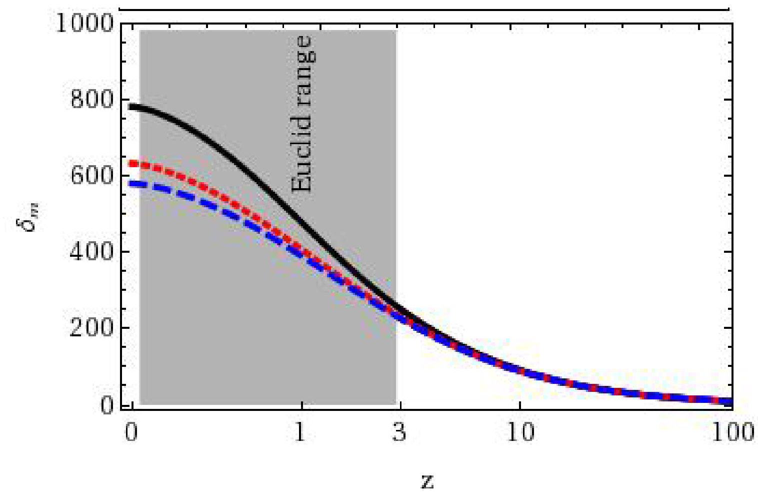
Modified Gravity predictions

$$\delta_k'' + (1+\frac{H'}{H})\delta_k' - \frac{3}{2}Q(k,a)\Omega_m\delta_k = 0$$

$$Q \approx 1 - \frac{1-\Omega_m}{3}$$

$$\frac{d\log\delta}{d\log a} = \Omega_m(a)^\gamma$$

$$\gamma_s = \frac{3(1-w)}{6w-5} \approx 0.55$$

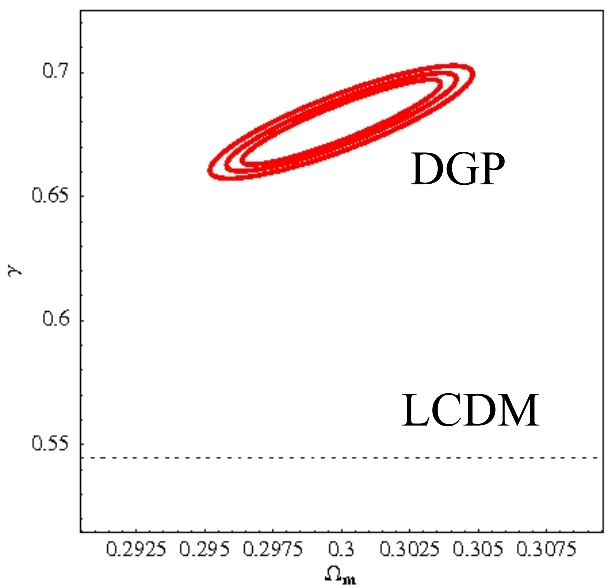


DGP $$\gamma \approx \gamma_s(1+\frac{1-Q}{(1-w)(1-\Omega_m)}) \approx 0.65-0.70$$

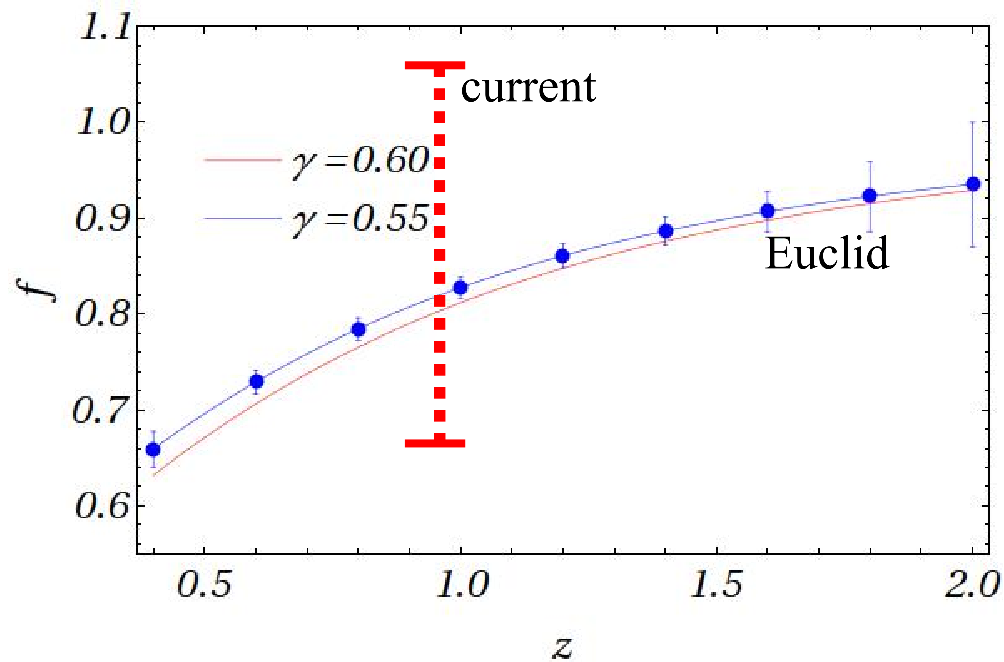
f(R) $$\gamma \approx \gamma_s(1+\frac{k^2a^2}{M(f)^2+k^2a^2}) \approx 0.40-0.55$$

clustered DE $$\gamma \approx \gamma_s\left[1+\frac{(1+w)a^{-3w}}{(1-w)\left(1-3w+\frac{k^2c^2{}_sa^2}{H^2{}_0\Omega_m}\right)}\right]$$

Euclid vs. gamma

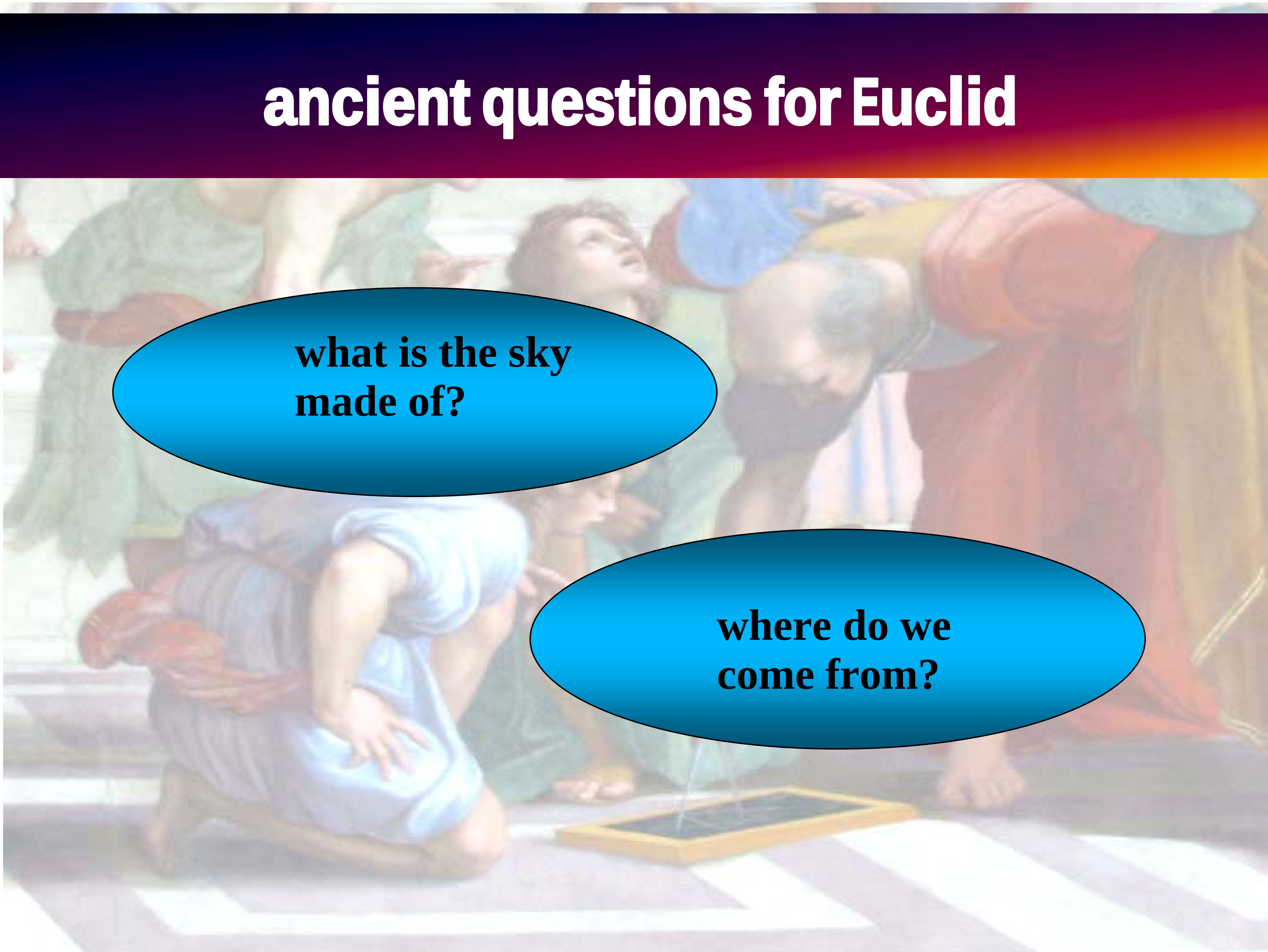


tomographic weak lensing



galaxy power spectrum
(redshift distortions)

ancient questions for Euclid



what is the sky made of?

where do we come from?

Euclid vs. dark matter

dark matter halos from weak lensing maps of clusters

dark matter abundance from power spectrum shape

dark matter clustering from cluster abundance

neutrino mass from power spectrum shape

Euclid cosmological bounty

Neutrino mass	error $m_\nu \approx 0.03\, eV$ error $N_\nu \approx 0.3$
Inflationary spectrum	error $n_s \approx 0.005$ error $\alpha \approx 0.05$
Primordial non gaussianity	error $f_{NL} < 5$

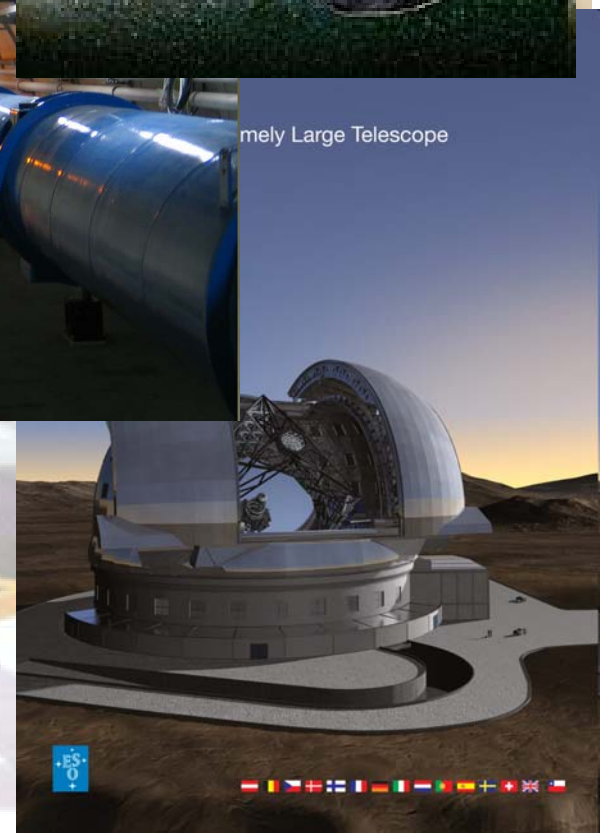
Euro-Synergy

Planck 2009

LHC 2009

Gaia 2011

EELT 2020



LHC (beyond the Higgs)

Standard model is complete but.....

no unification of forces and particles

Answer: supersymmetry

Consequence for cosmology:
the lightest
supersymmetric particle is a
perfect cold dark matter candidate

no consistent inclusion of gravity

Answer: string theory

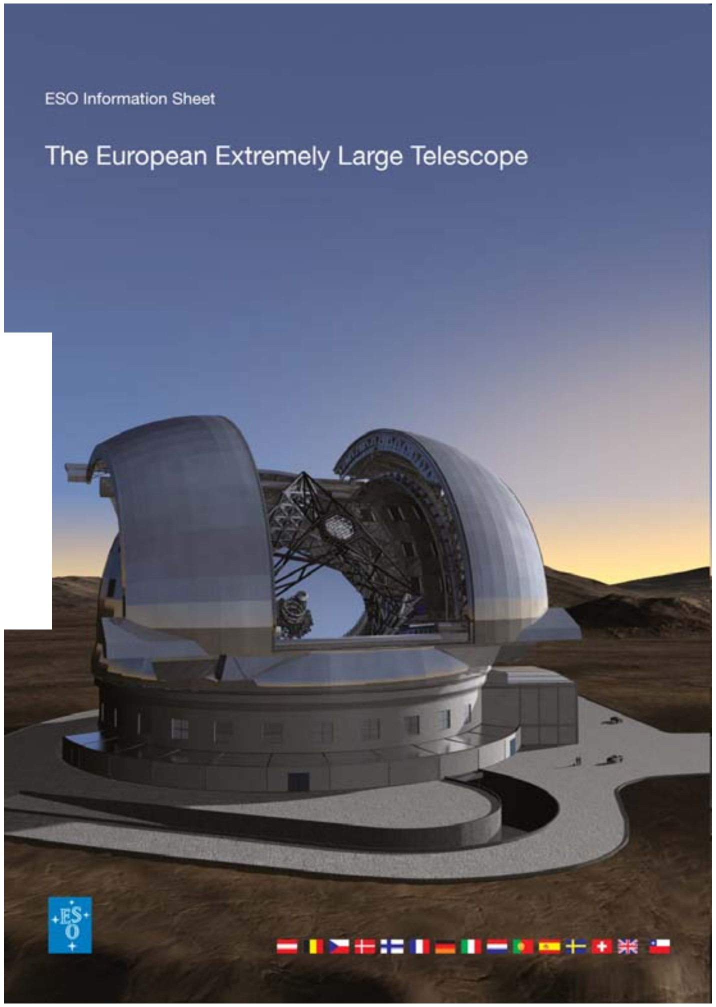
Consequence for cosmology:
the gravity leakage
into the extra-dimensions required by
strings could explain acceleration

EELT

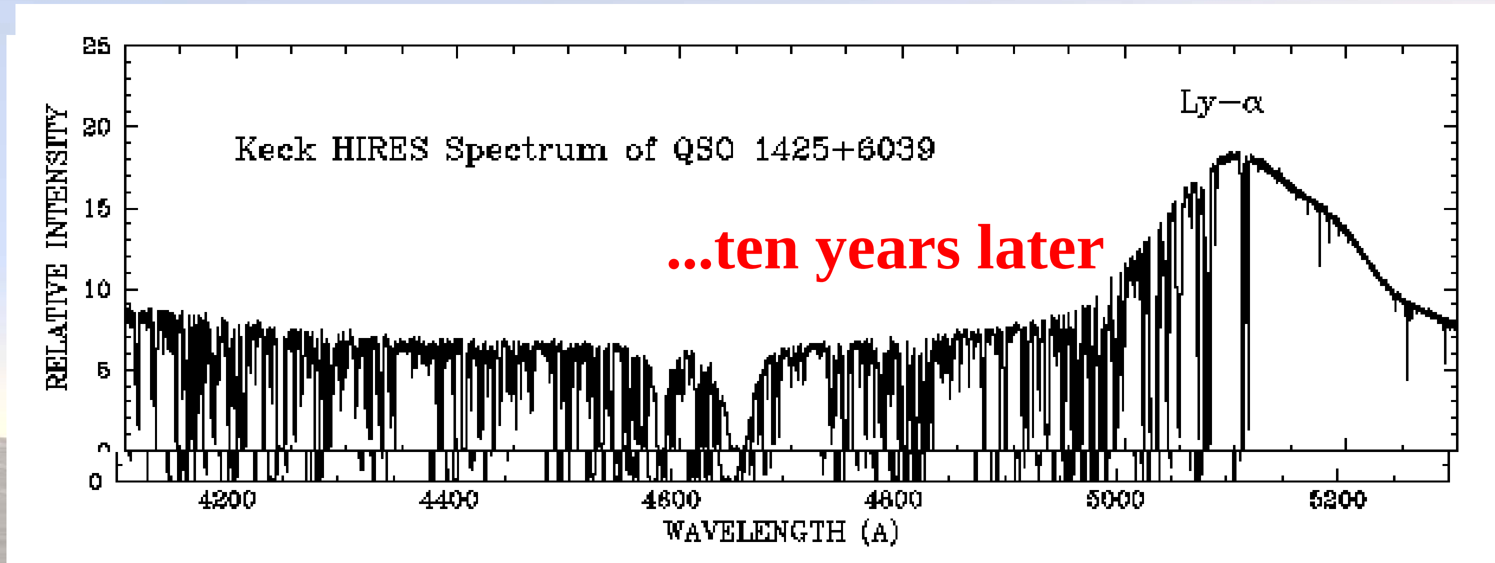
THE EXTREMELY LARGE TELESCOPE

IS THE ESSENTIAL NEXT STEP IN MANKIND'S DIRECT OBSERVATION OF THE NATURE OF THE UNIVERSE.

IT WILL PROVIDE THE DESCRIPTION OF REALITY WHICH WILL UNDERLIE OUR DEVELOPING UNDERSTANDING OF ITS NATURE.



EELT



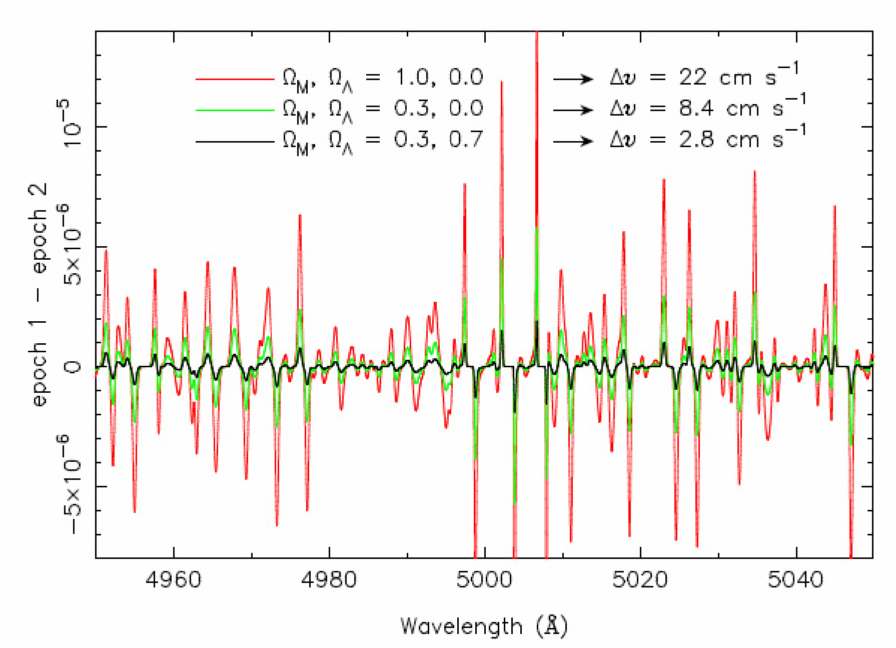
Sandage effect

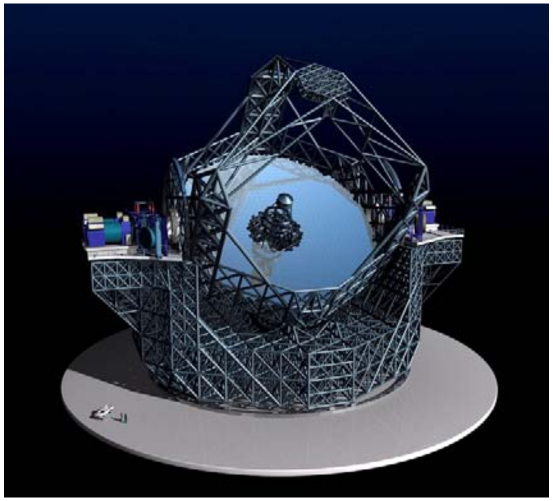
$$\Delta z \approx \frac{a(t_0+\Delta t_0)}{a(t_s+\Delta t_s)} - \frac{a(t_0)}{a(t_s)}$$

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

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

CODEX at EELT





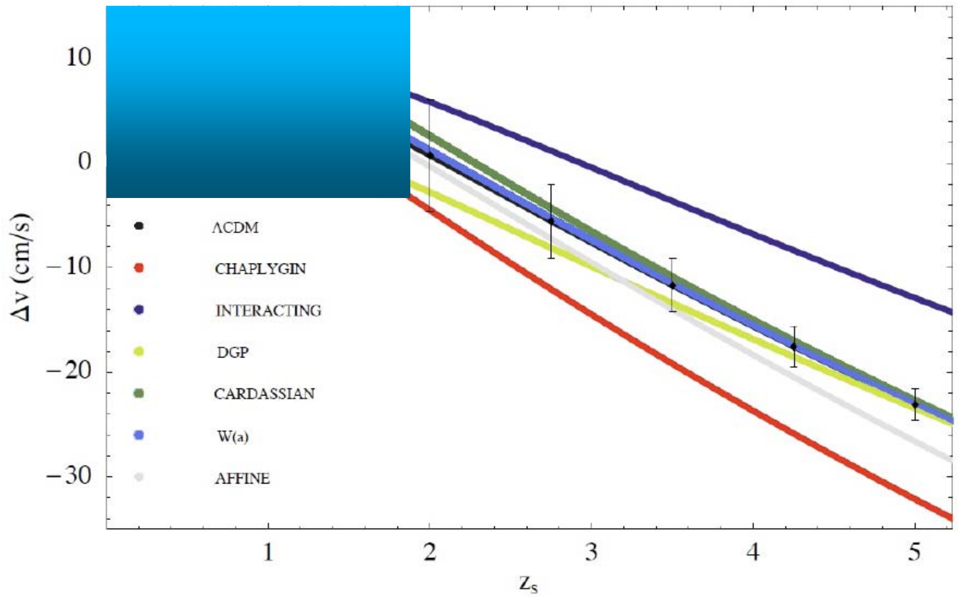
- large colleting area
- high resolution spetrographs
- stable, low-peculiar motion

targets: Lyman-alpha lines

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

Liske et al. 2008

Euclid range



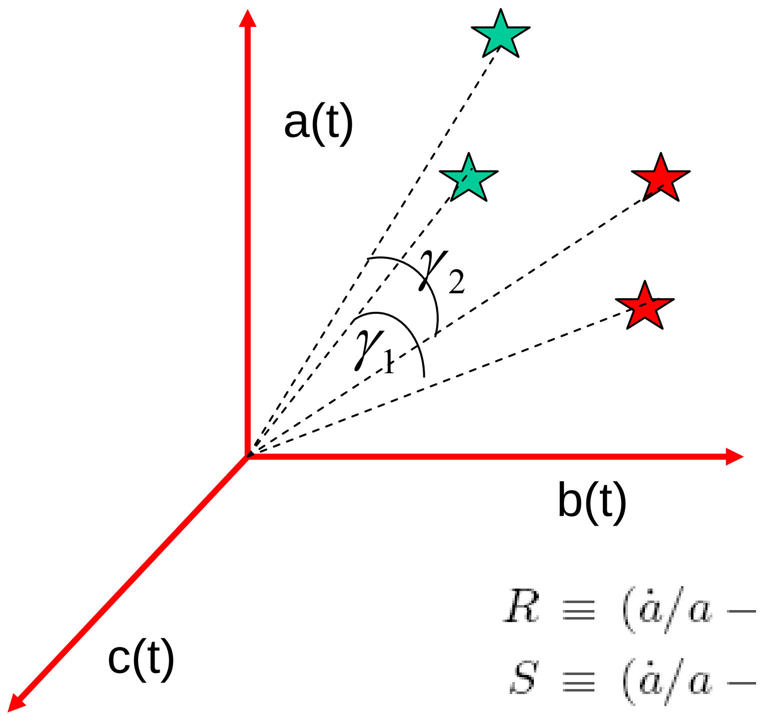
Balbi & Quercellini 2007

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
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

The cosmic reference frame

Bianchi I



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

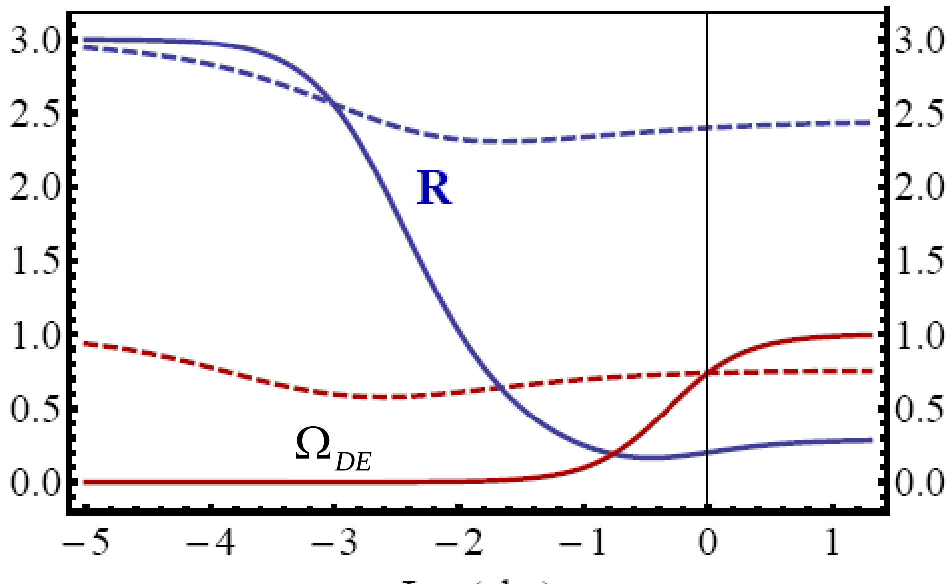
Anisotropic dark energy

Mota & Koivisto 2008,
Barrow, Saha, Bruni, Rodrigues and many others..

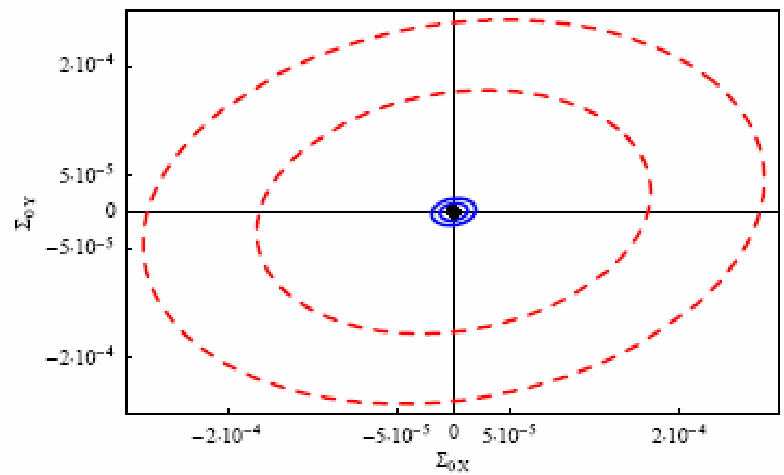
$$T^{\mu}_{(\mathrm{DE})\nu} \;=\; \mathrm{diag}(-1, w, w+3\delta, w+3\gamma)\rho_{\mathrm{DE}},$$

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

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



C. Quercellini, P. Cabella, L.A.,
M. Quartin, A. Balbi 2009



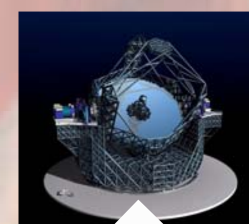
$$R = \frac{\Delta H}{H} \leq 10^{-4} \quad , \underline{\textit{at any z}}$$

A European Dream Team

• The combination of weak lensing and clustering allows the full recostruction of the space-time geometry
• In addition, Euclid will provide unique new constraints on dark matter and initial conditions
• Togther with Planck, LHC, Gaia, EELT, Euclid will draw a new 3D atlas of the universe

Euclid

LHC

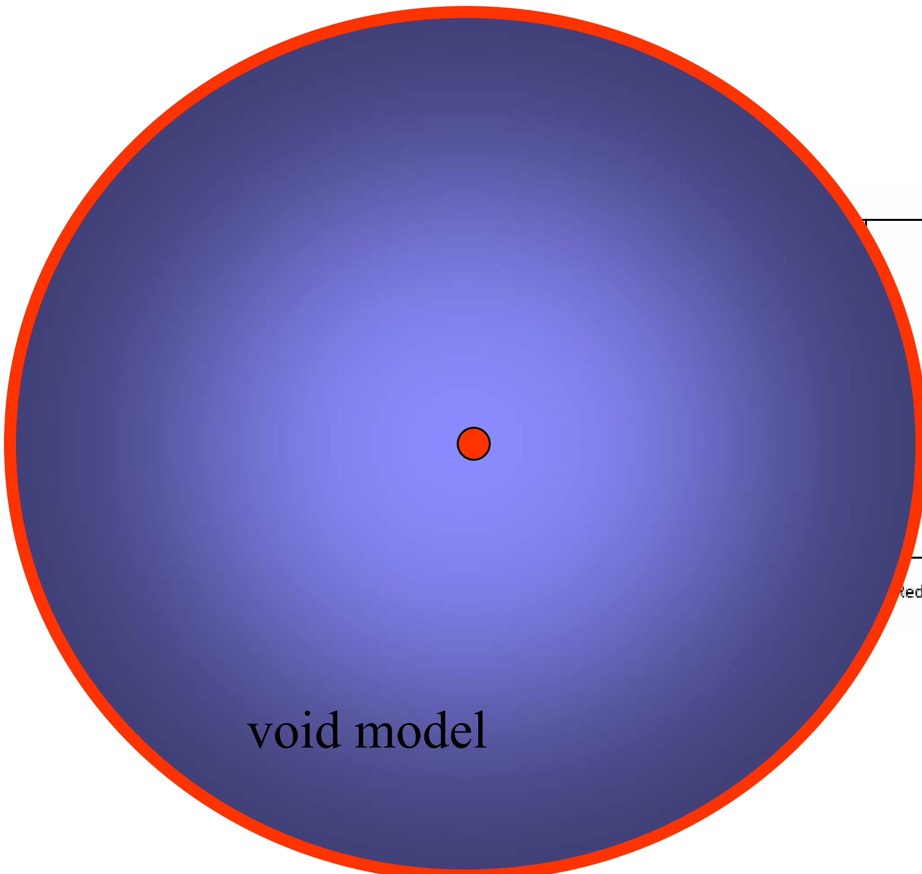


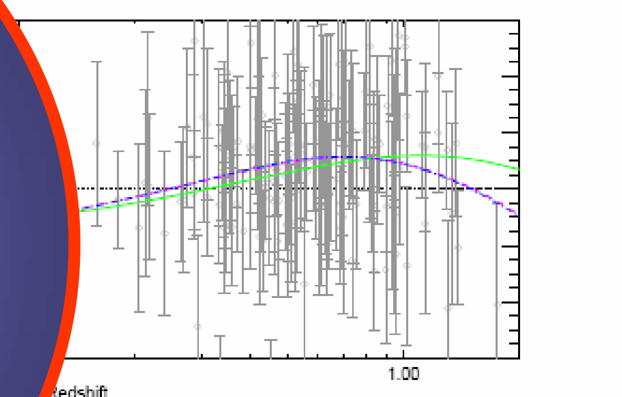
EELT

Gaia

Cosmic Degeneracy 3

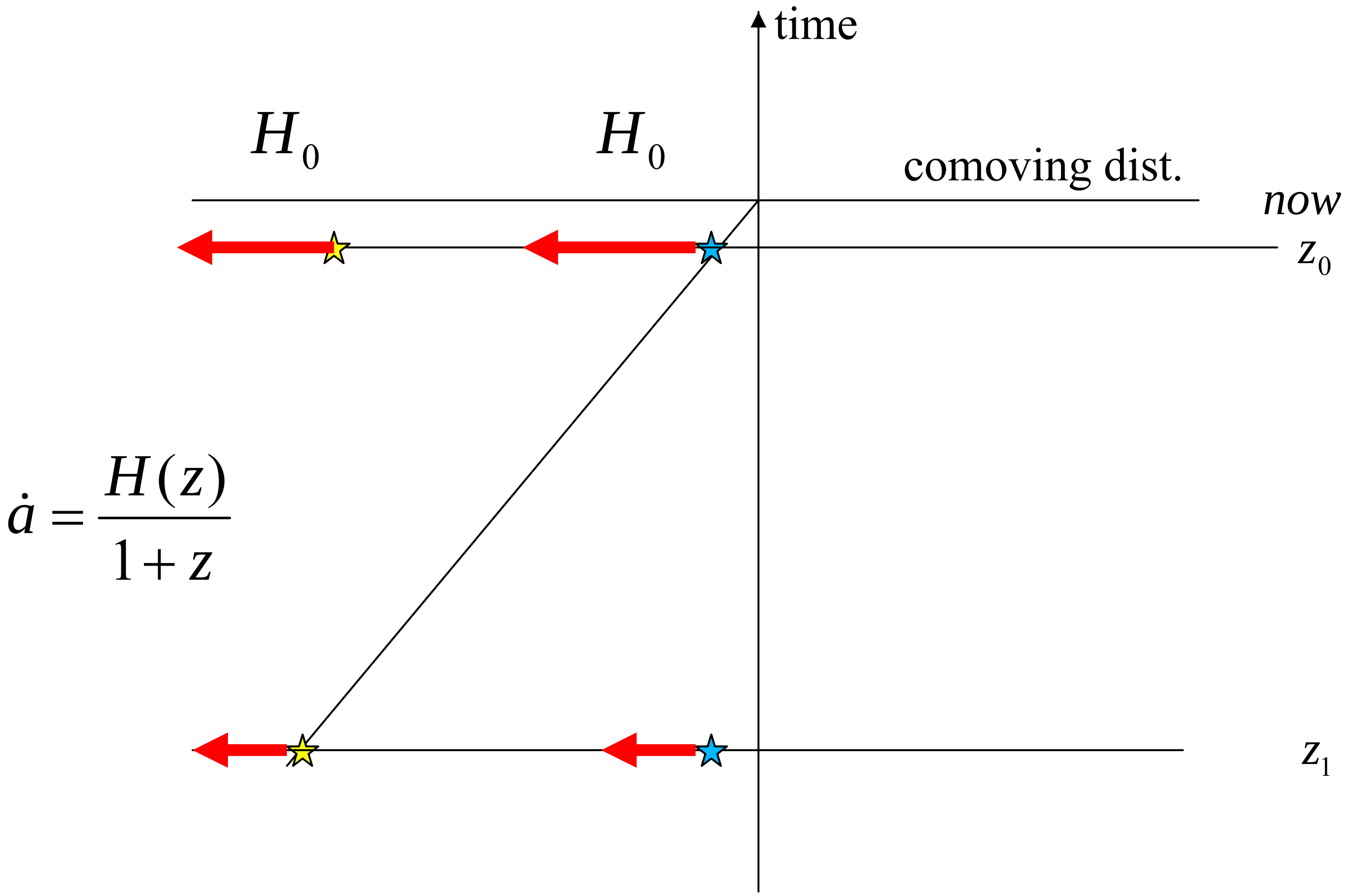
Tomita 2001
Celerier 2001
Alnes & Amarzguioi 2006,07
Bassett et al. 07
Clifton et al. 08
Notari et al. 2005-08
Marra et al. 08
Garcia-Bellido & Haugbolle 2008



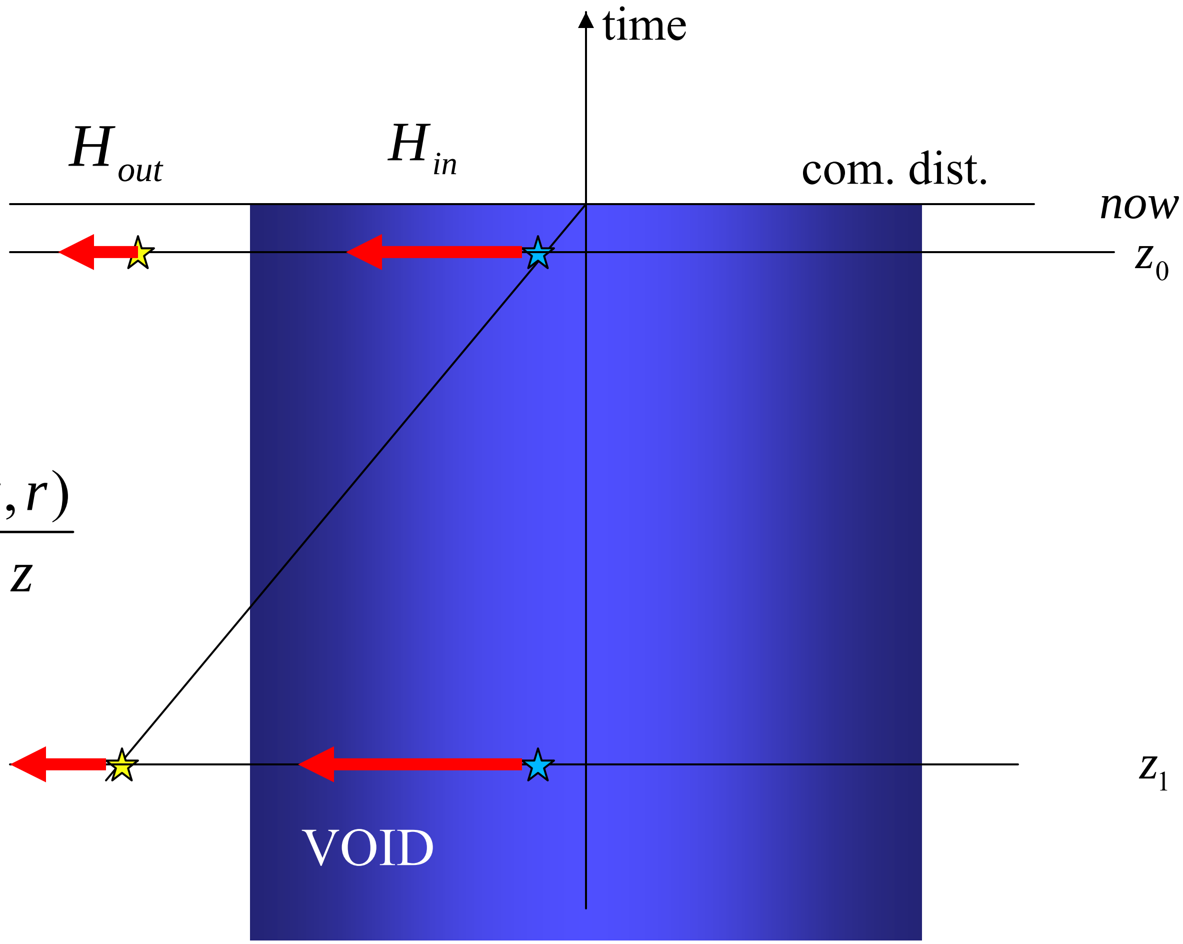


Garcia-Bellido & Haugbolle 2008

One null cone

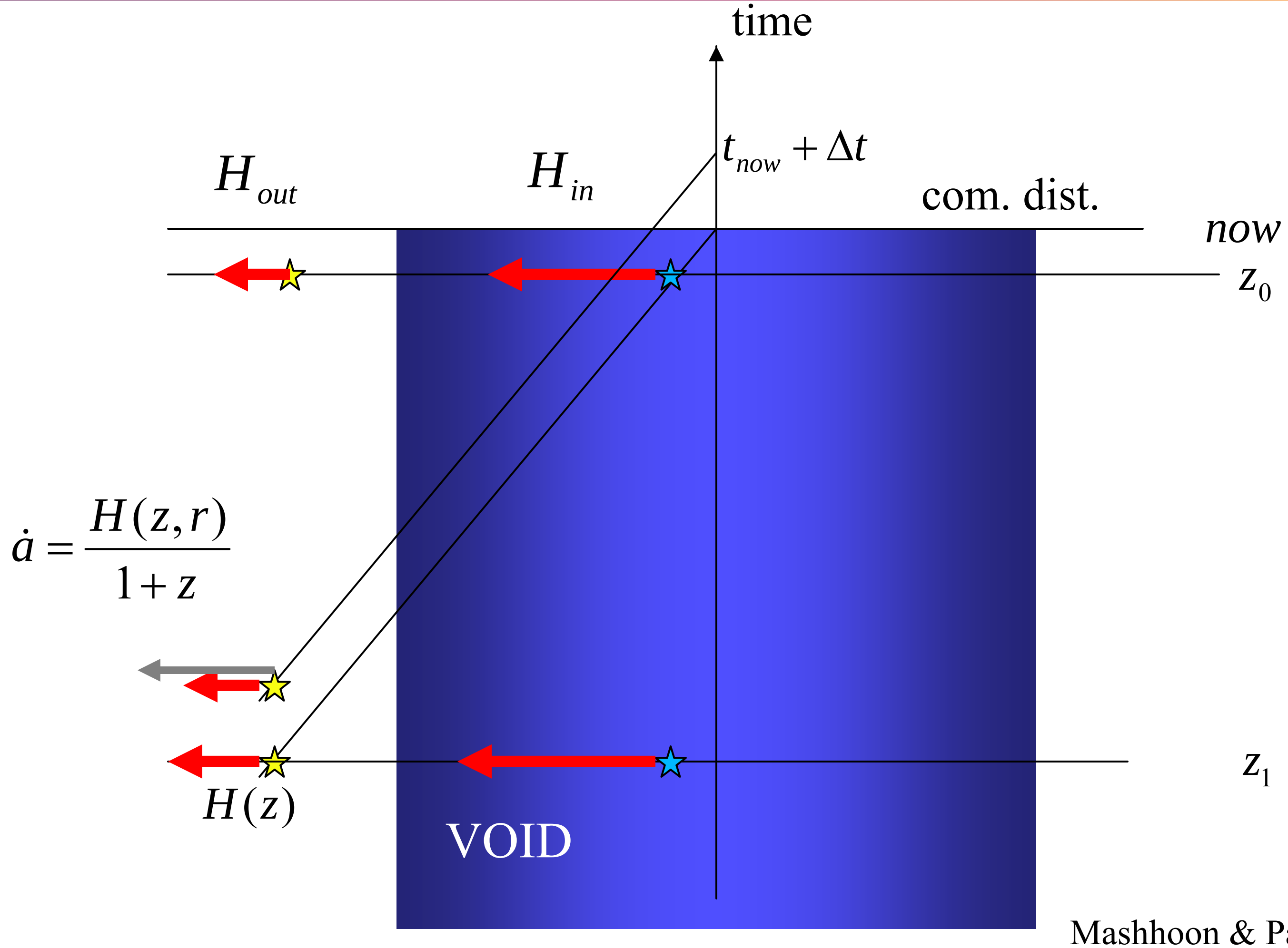


One null cone



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

Two null cones are better than one!



ESTEC 2009

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

Cosmology and modified gravity

in laboratory

in the solar system

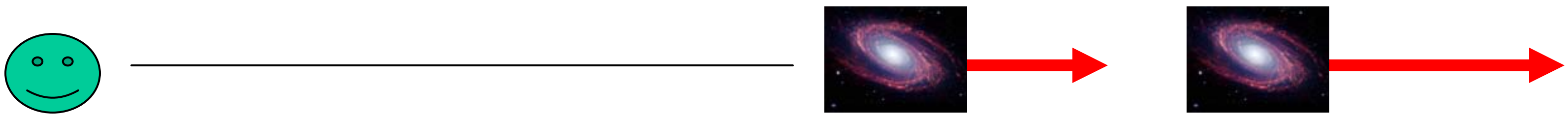
very limited time/space/energy scales; only baryons

at astrophysical scales

complicated by non-linear/non-gravitational effects

at cosmological scales

unlimited scales; mostly linear processes; baryons, dark matter, dark energy !



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

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.

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

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

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

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

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

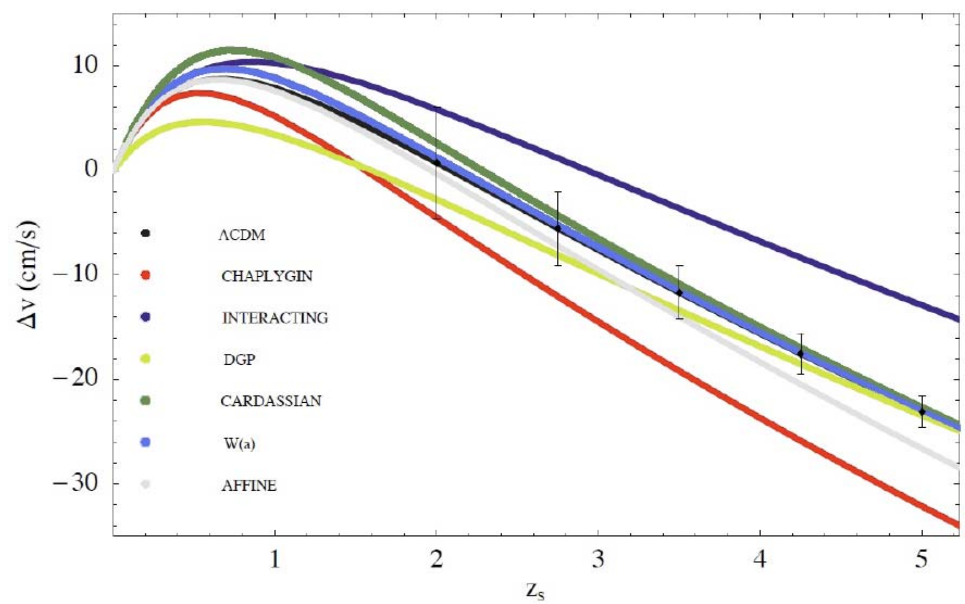
$$H_0 \Delta t \approx 10^{-9} \quad (10\,yrs)$$

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

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

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

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



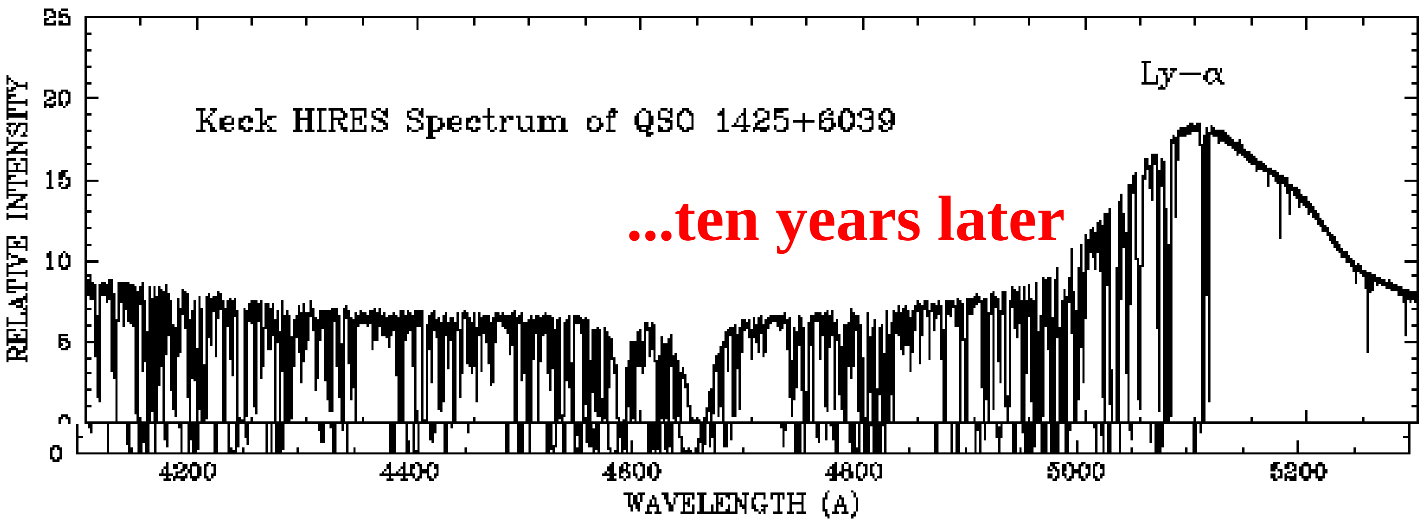
Corasaniti, Huterer, Melchiorri 2007
Balbi & Quercellini 2007

The Extremely Large Telescope

is the essential next step in mankind's direct observation of the nature of the universe.

It will provide the description of reality which will underlie our developing understanding of its nature.

CODEX at EELT



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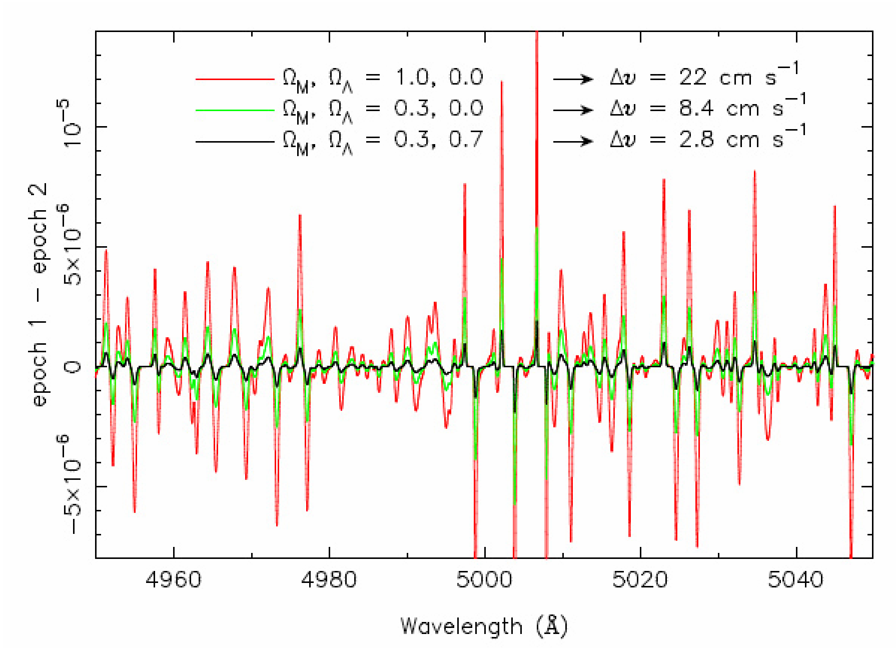
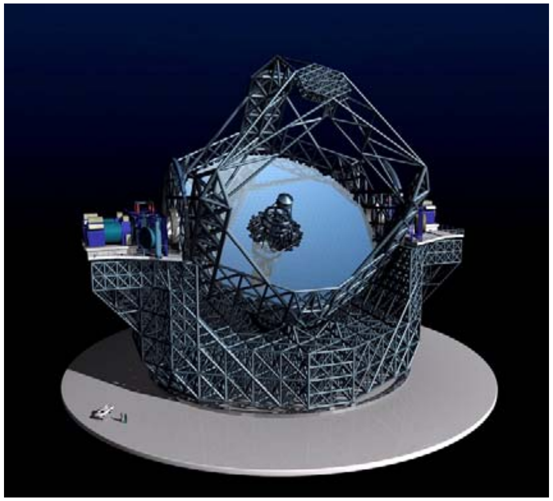




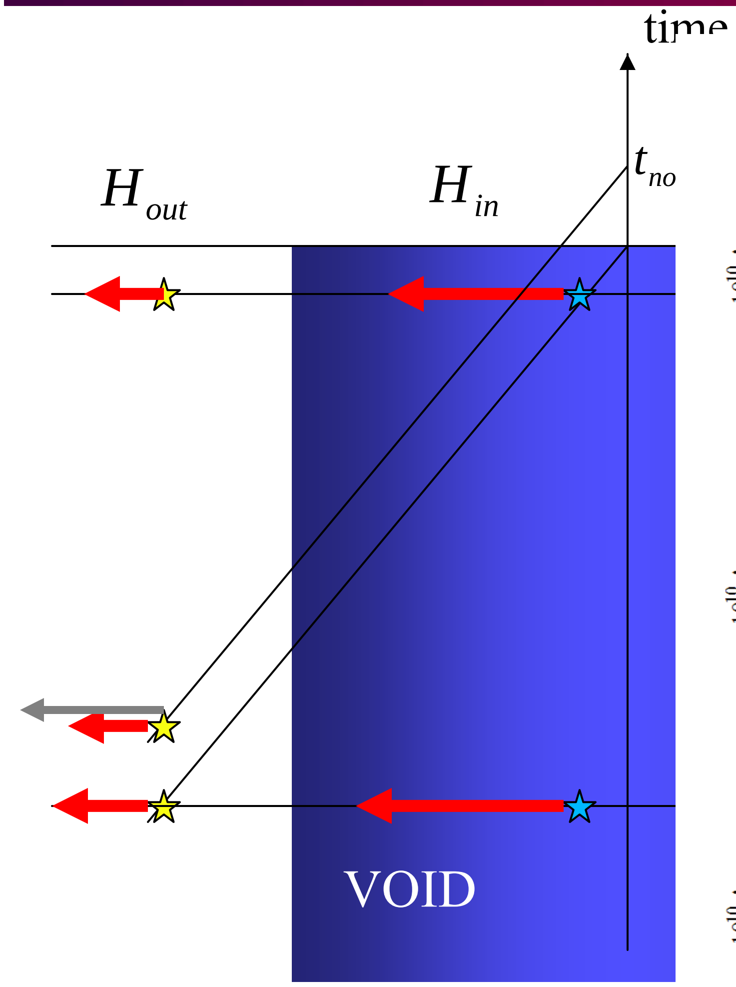
- large colleting area
- high resolution spetrographs
- stable, low-peculiar motion

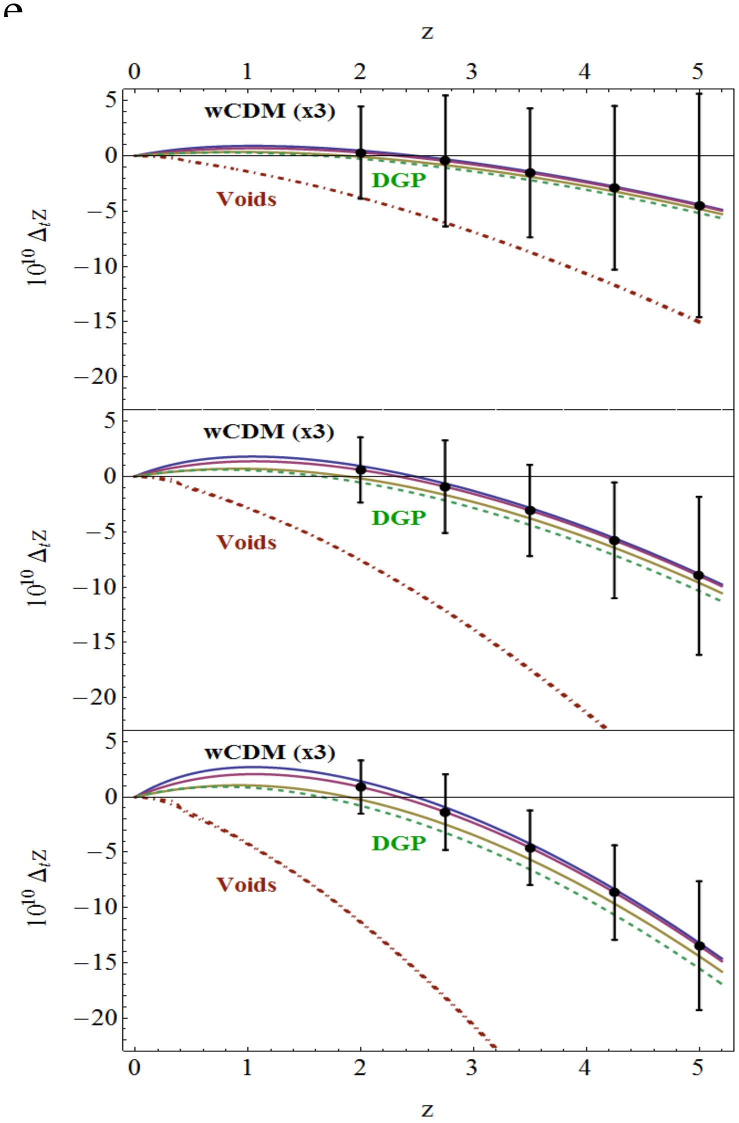
targets: Lyman-alpha lines

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

Liske et al. 2008

Two null cones are better than one!





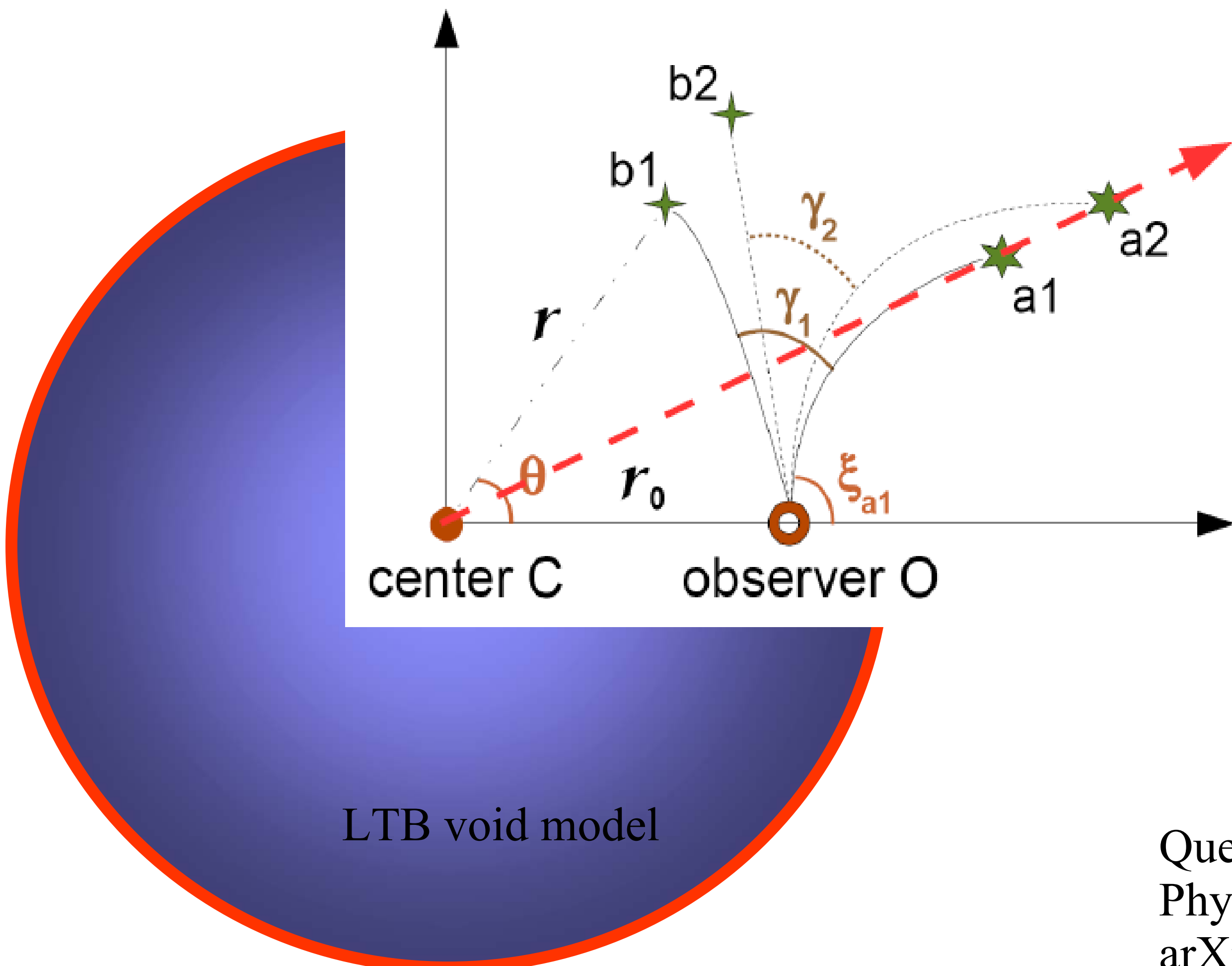
M. Quartin & L. A. 2009

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

Lemaître-Tolman-Bondi models

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

- LTB metrics describe void models

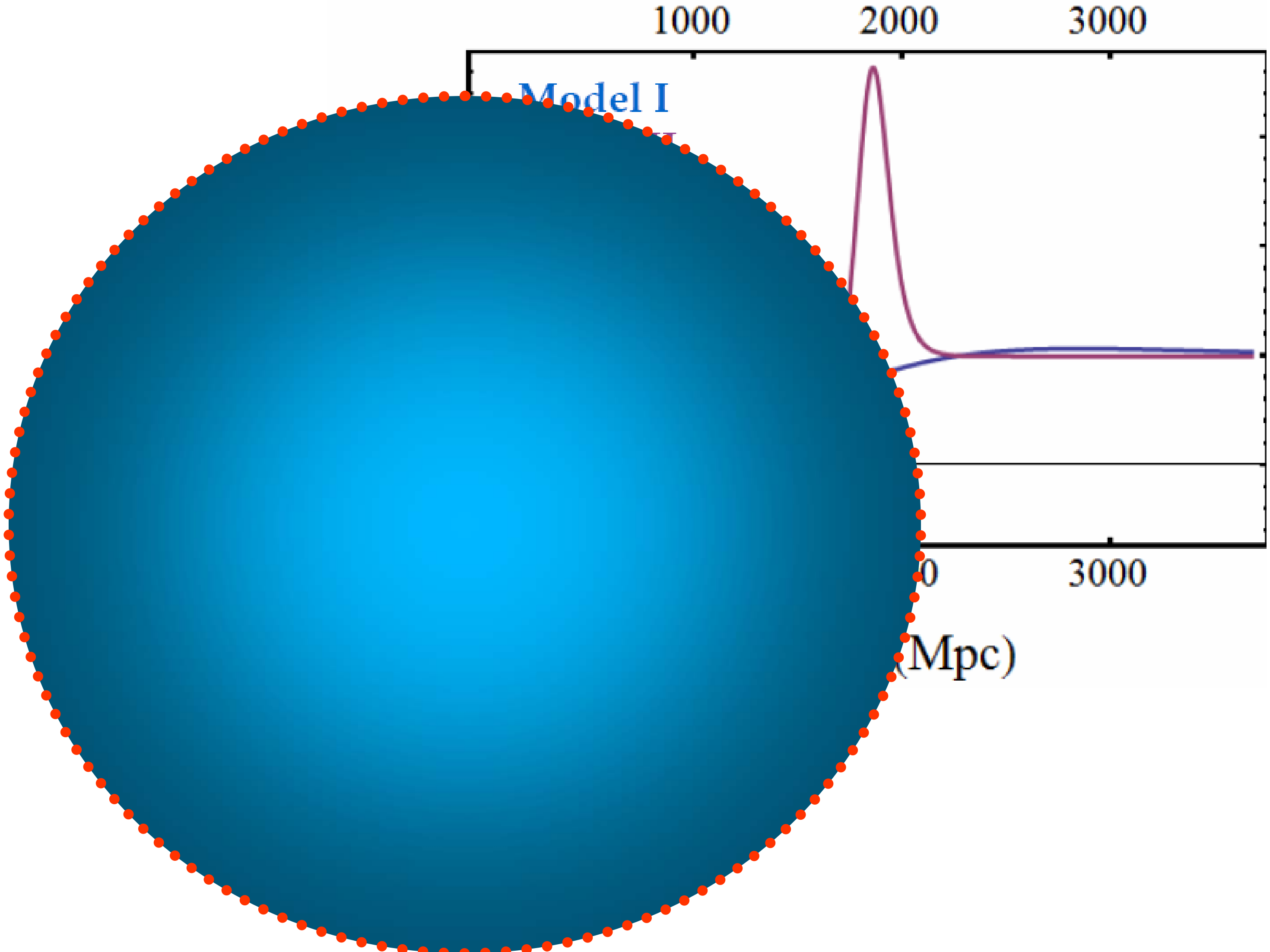
$$ds^2 = -dt^2 + \frac{[R'(t,r)]^2}{1+\beta(r)}dr^2 + R^2(t,r)d\Omega^2$$

- Exact solution in a matter-dominated era

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

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

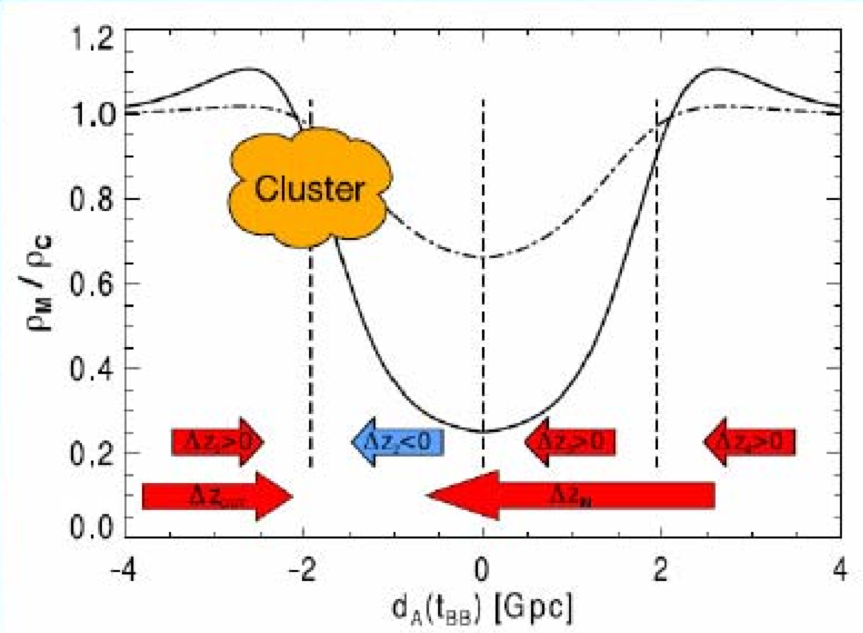
LTB models



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 $z \approx .3$)



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 & $\Delta\theta$.

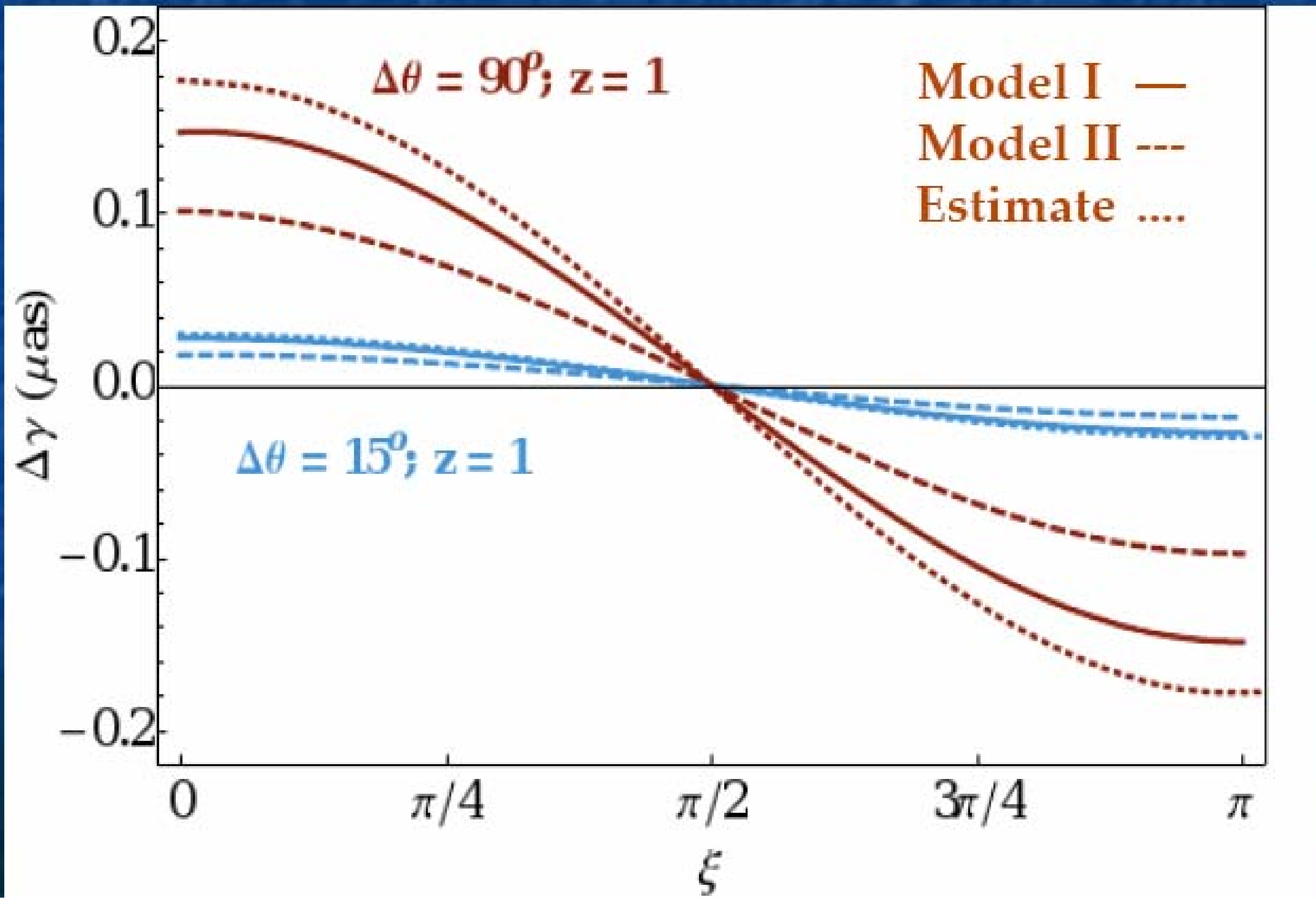
$$\Delta_t \gamma \simeq \Delta t \left(\overline{H}_{\mathrm{obs}} - \overline{H}_X\right) \frac{X_{0\mathrm{bs}}}{X} \left(\cos\theta \, \Delta\theta + \sin\theta \, \frac{\Delta X}{X} \right)$$

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
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 $\geq 450{,}000$ (conservative)

Noise and Sistematics

- Most obvious source of noise → peculiar velocities

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

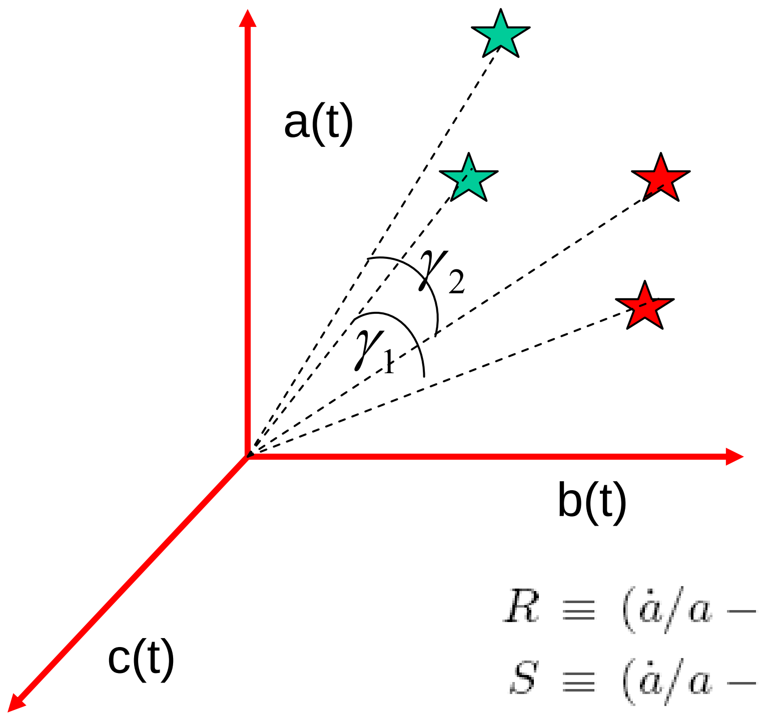
- Most serious source of noise → changing aberration due to acceleration of the solar system

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 on anisotropy

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

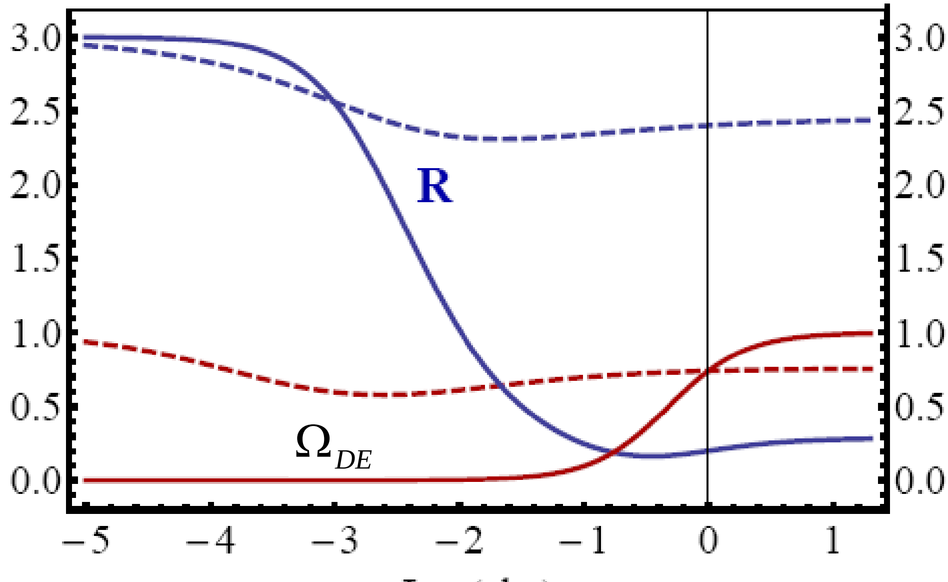
Anisotropic dark energy

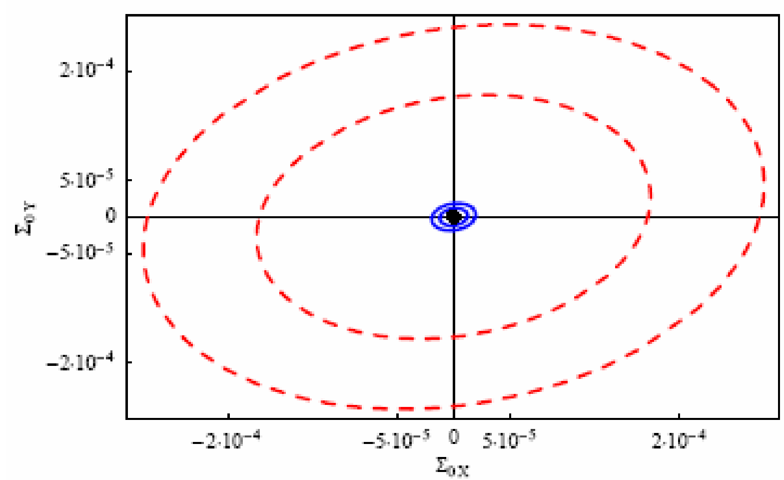
Mota & Koivisto 2008,
Barrow, Saha, Bruni, Rodrigues and many others..

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

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

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





C. Quercellini, P. Cabella, L.A.,
M. Quartin, A. Balbi 2009

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

WERBUNG

DARK ENERGY
theory and observations

Contents

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L. A. and S. Tsujikawa
Cambridge University Press
mid 2010

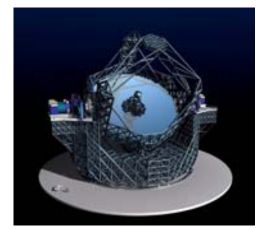
ESTEC 2009

Breaking the degeneracies

- The task of understanding the nature of Dark energy is plagued by several cosmic degeneracies
- 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

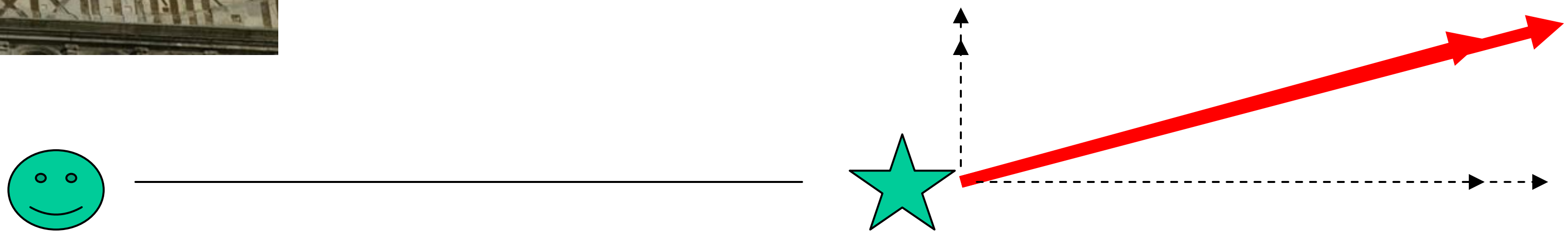
full 3D picture of cosmic kinematics !

Euclid



EELT

Gaia



	radial	transverse
global		
local		

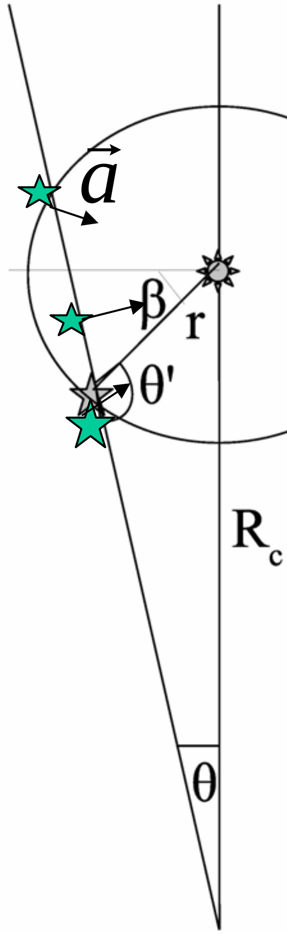
Real-time Cosmology

	radial	transverse
global	Expansion rate	anisotropy
local	Gravity at galactic scales: eg Newton vs Modif. Grav.	

ToDo

figura redshiftdrift void
figura cover book

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

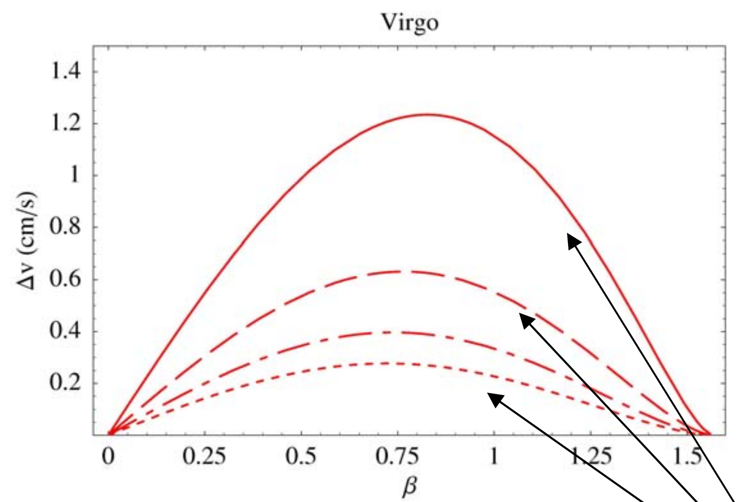
$$\rho_{NFW}(r) = \frac{\delta_c \rho_c}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}, \quad r_s = r_v / c$$

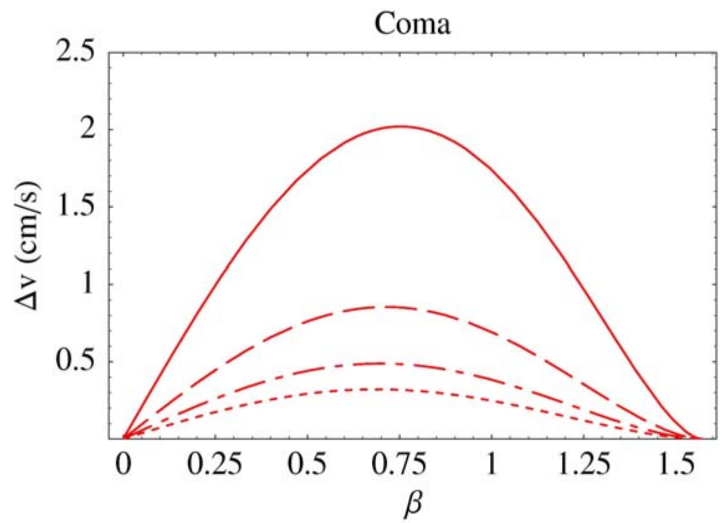
$$s(\beta) = \Delta v = \left(2\frac{cm}{\sec}\right)\sin\beta \frac{\Delta t}{10yr}\frac{M_v}{10^{14}M_\Theta}\left(\frac{r_s}{0.5Mpc}\right)^{-2} C\left(\frac{\log(1+\frac{r}{r_s})}{(r/r_s)^2} - \frac{1}{\frac{r}{r_s}(1+\frac{r}{r_s})}\right)_{r=R_c\theta/\cos\beta}$$

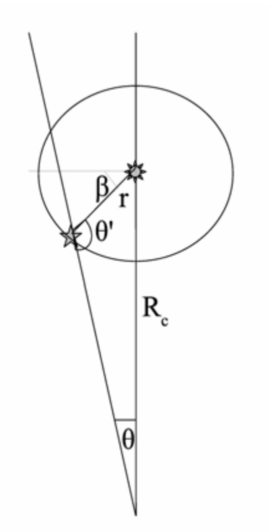
	Mass	r_s
Andromeda	10^{11}	20 kpc
Virgo	1.2×10^{15}	0.55 Mpc
Coma	1.2×10^{15}	0.29 Mpc

Peculiar Acceleration

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



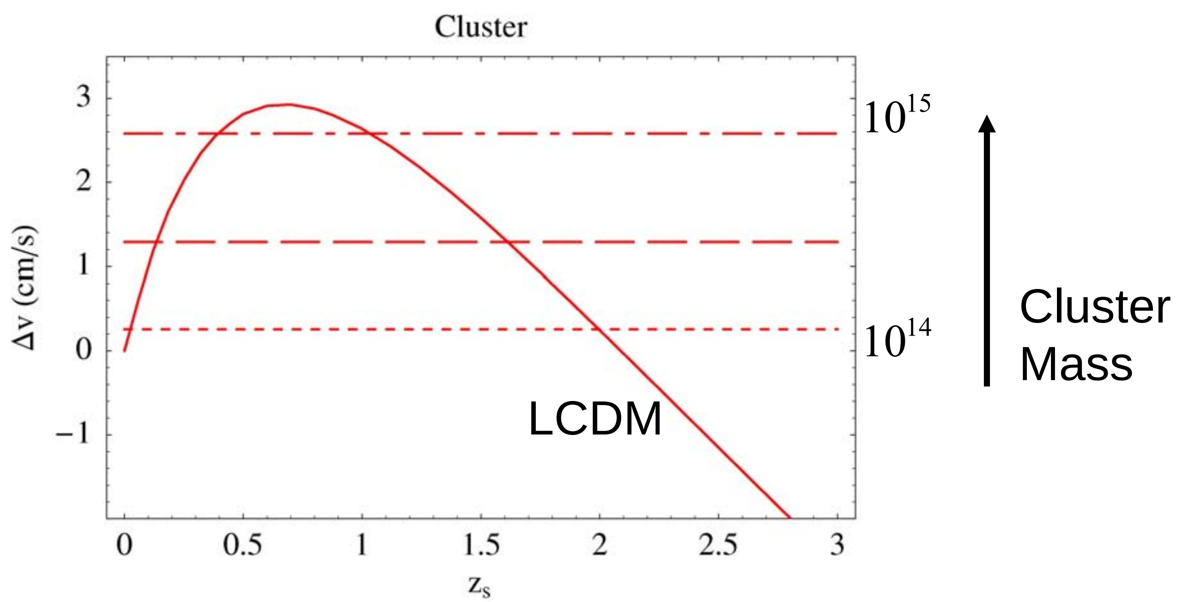




different
lines of sight

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,

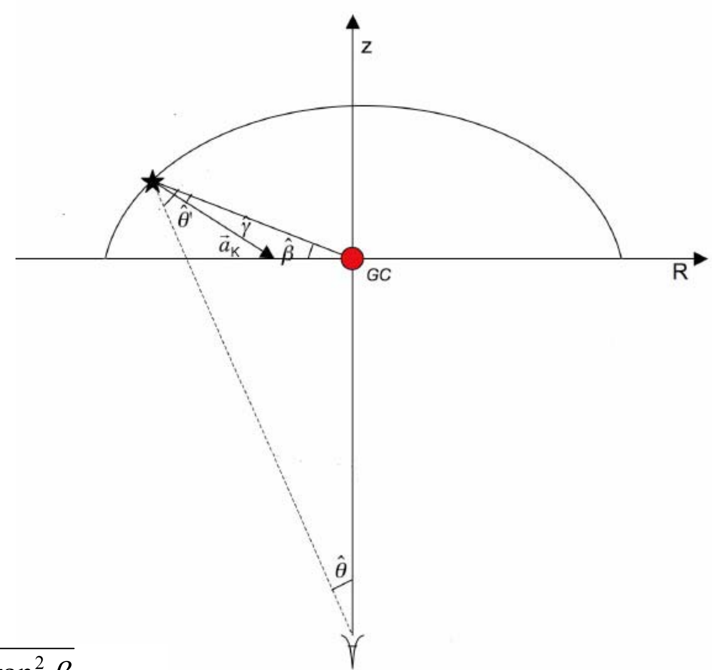
$$\phi_K = -\frac{MG}{\left[R^2 + (|z|+h)^2\right]^{1/2}} \qquad a_K = -\frac{MG}{\left[R^2 + (|z|+h)^2\right]}$$

- 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:

$$a_{s,K} = \frac{MG}{R_g^2\theta^2\left[1 + \left(|\tan\beta| + \frac{h}{R_g\theta}\right)^2\right]}\sin(\beta \mp \gamma) \qquad a_{s,L} = \frac{v_0^2 R_g \theta \sqrt{1 + \frac{\tan^2\beta}{q^2}}}{R_c^2 + R_g^2\theta^2\left(1 + \frac{\tan^2\beta}{q^2}\right)}\sin\beta$$



C. Quercellini, L.A., A. Balbi 2008

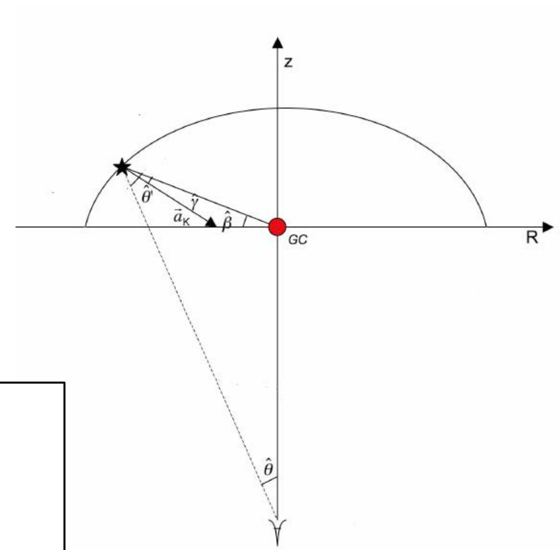
arXiv:0807.3237

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

Spiral galaxy: MOND

- Beckenstein-Milgrom modified Poisson equation

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



- peculiar acceleration in MOND:

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

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

9

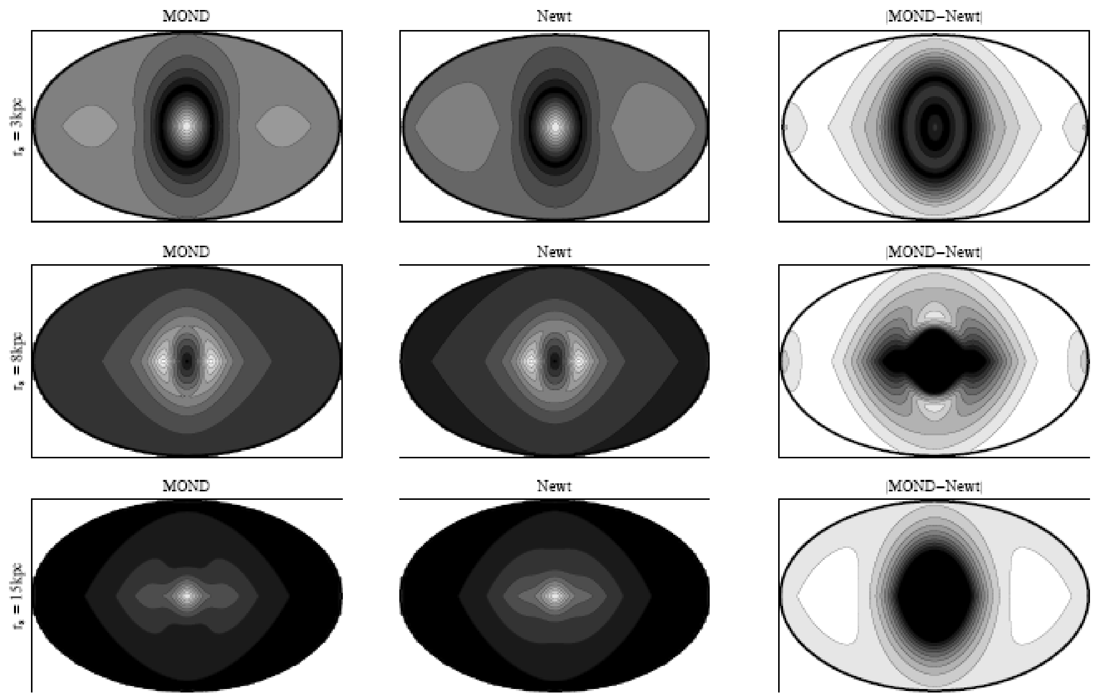


FIG. 10: Comparison in the velocity shift signal (for T=15 years) as seen in the sky from our position in the Milky Way, for the MOND, CDM halo configuration, and their difference (left to right) and for three distances from the Sun (3, 8 and 15 kpc, top to bottom). The sky signal is plotted in galactic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

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 !