Gaia, Cosmic Parallax and Real-Time Cosmology

Quercellini, Quartin & Amendola 0809.3675 (PRL)

Quercellini, Cabella, Amendola, Quartin & Balbi 0905.4853

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Teaser

- Near future high-precision telescopes and satellites will vastly improve our knowledge of the universe
- Unprecedented accuracy, broadness and completeness invites us to think outside the box
- Not necessarily only on crazy ideas...
- … but also on *semi-crazy* ideas.

Homogeneity and Isotropy

- The most basic (and old) tenets of cosmology
- FLRW metric:
  - most general homogeneous and isotropic metric
  - overwhelmingly successful at describing the universe in large-scales
  - *Consistent* with all current observations
- Hard to probe directly → *lightcone* vs. *const. time* slices:
  - Possibility →more exotic models may also be *consistent* with data
    - e.g.: void models

Lemaître-Tolman-Bondi models

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

- LTB metrics describe void models

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

- Exact solution in a matter-dominated era

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

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

LTB models (2)

- The Alnes et al. *(astro-ph/0607334)* class of LTB models:

$$\alpha(r) = \left(H^{\mathrm{out}}_{\perp,0}\right)^2 r^3 \left[1 - \frac{\Delta\alpha}{2}\left(1 - \tanh\frac{r - r_{\mathrm{vo}}}{2\Delta r}\right)\right]$$

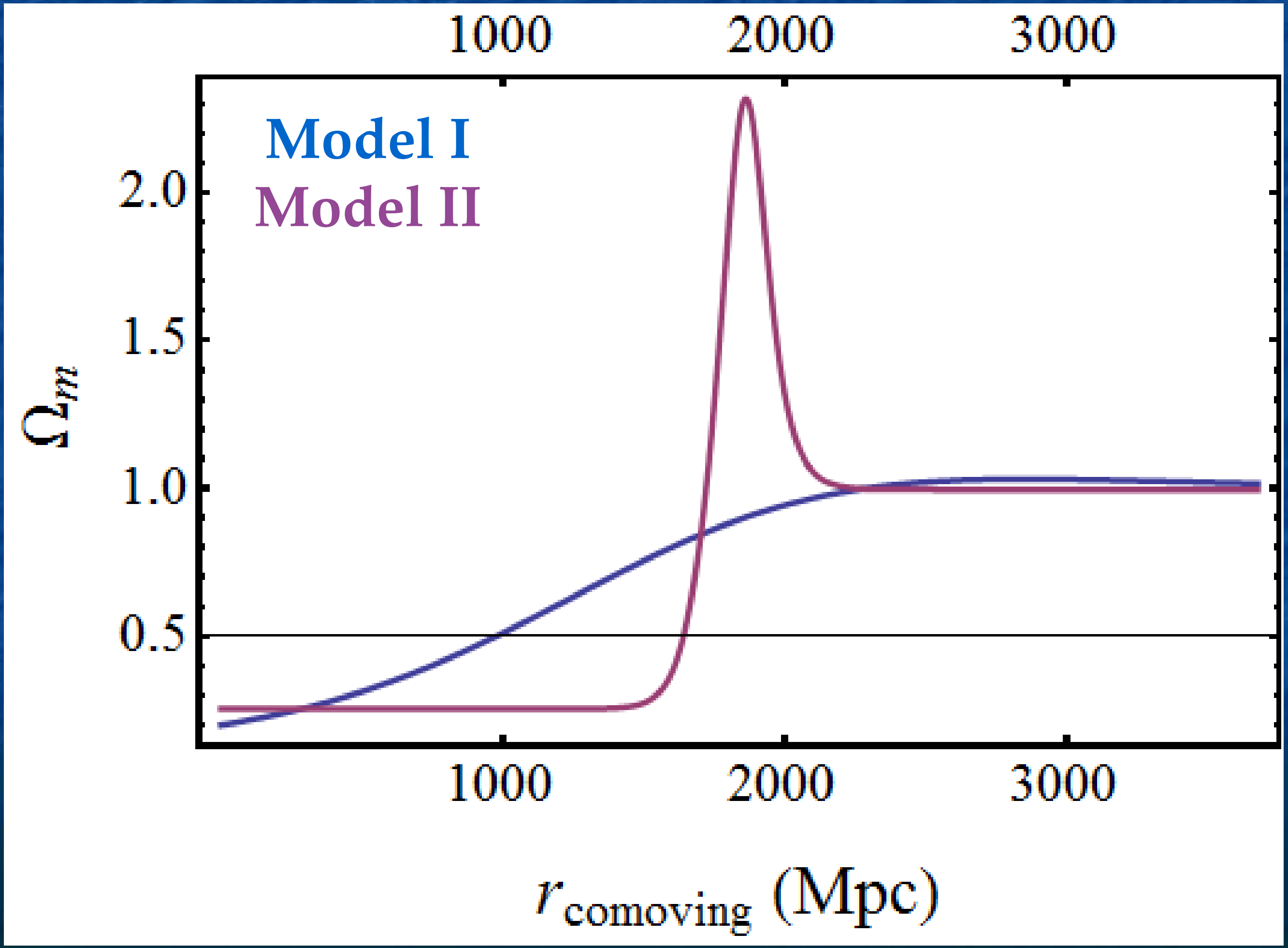
$$\beta(r) = \left(H^{\mathrm{out}}_{\perp,0}\right)^2 r^2 \frac{\Delta\alpha}{2}\left(1 - \tanh\frac{r - r_{\mathrm{vo}}}{2\Delta r}\right)$$

- We will consider 2 such models:
  - similar void sizes (z ~ .3)
  - different values of Δr

transition width

LTB models (3)

- Void caracteristics



Why study void models?

- Voids such as the ones showed can mimic the Hubble diagram without the need for dark energy!
  - Acceleration $\rightarrow$ artifact of wrong assumption on homogeneity
- Correct placement of 1^{st} peak of CMB*
- Not over complicated
- Could arise from...

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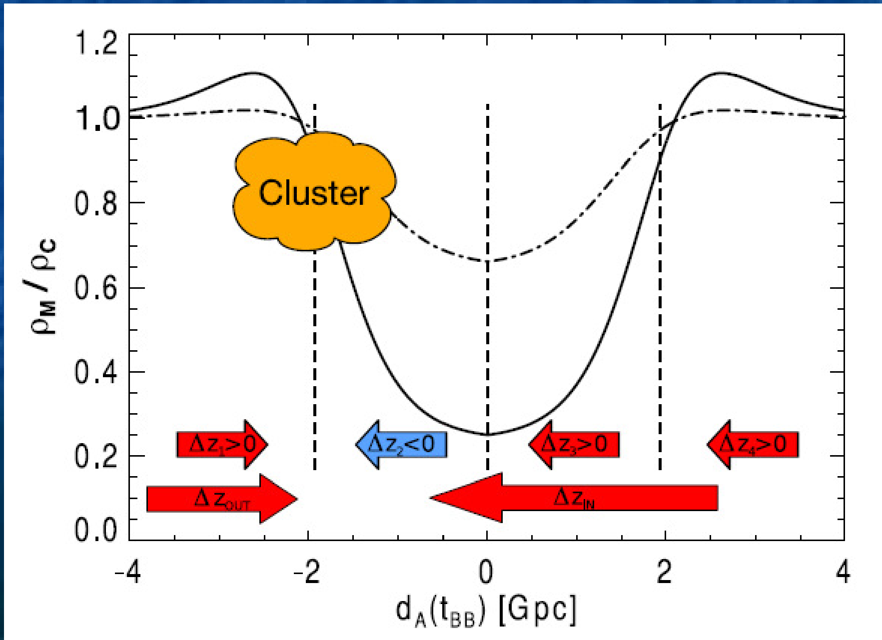
- Not over complicated
- Could arise from
  - back-reaction effects → one of many bubbles
  - eternal inflation scenarios
- Isotropic, if observer is in the center
  - No a priori reason for that* → unlikely!

Constraints on Void Models

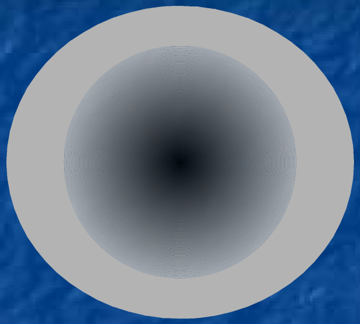
- Large voids (> 1.5 Gpc) are in conflict with
  - CMB blackbody spectrum
    - *Caldwell & Stebbins: 0711.3459 (PRL)*
  - Kinematic Sunyaev-Zeldovich effect from large clusters
    - *García-Bellido & Haugbolle: 0807.1326 (JCAP)*

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



Let iT Be

- LTB – Lemaître-Tolman-Bondi



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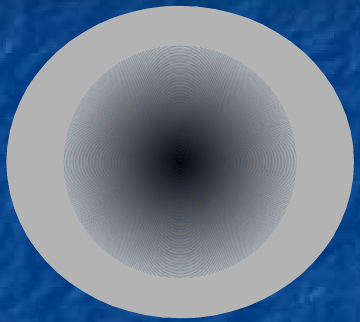
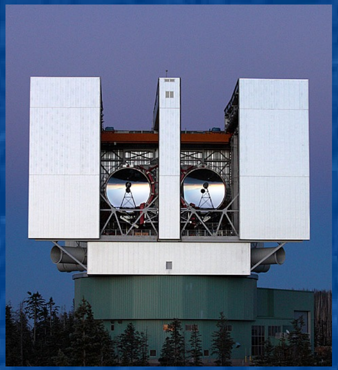


- LBT – Large Binocular Telescope



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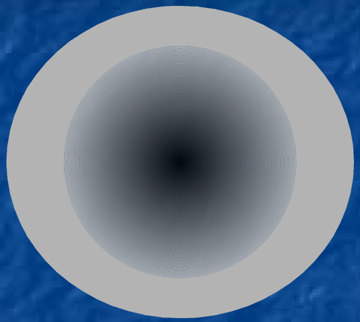

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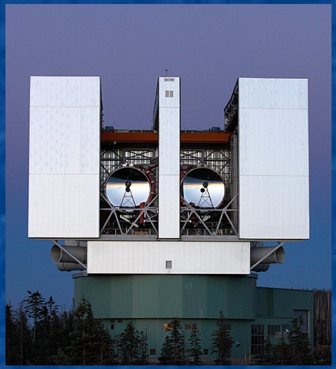
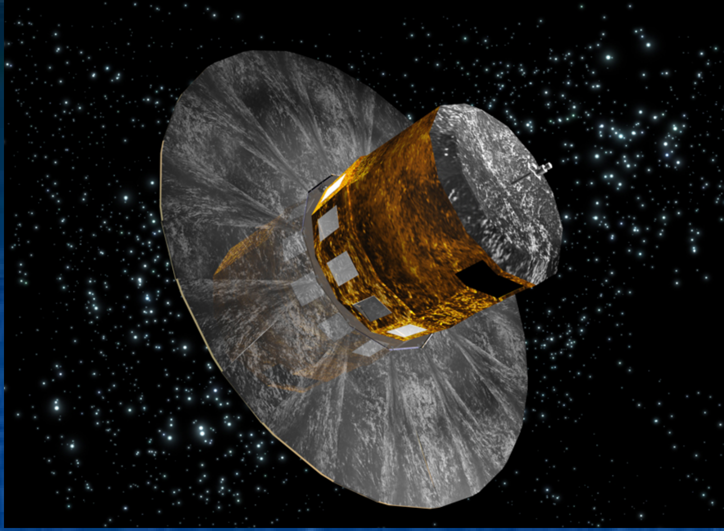


- BLT – Bacon Lettuce Tomato

Gaia in 1 slide



Launch: Dec 2011

- Gaia will achieve:
  - astrometry measurements with an accuracy of about 10 – 200 μas
  - a catalogue of approximately one billion stars to magnitude 20.
  - astrometric measurements of some 500,000 distant quasars
- Broad scientific goals
- Allows us to detect large-scale deviations from isotropy through observations of changes in the angular separation between sources at cosmic distances in a 5-year time period

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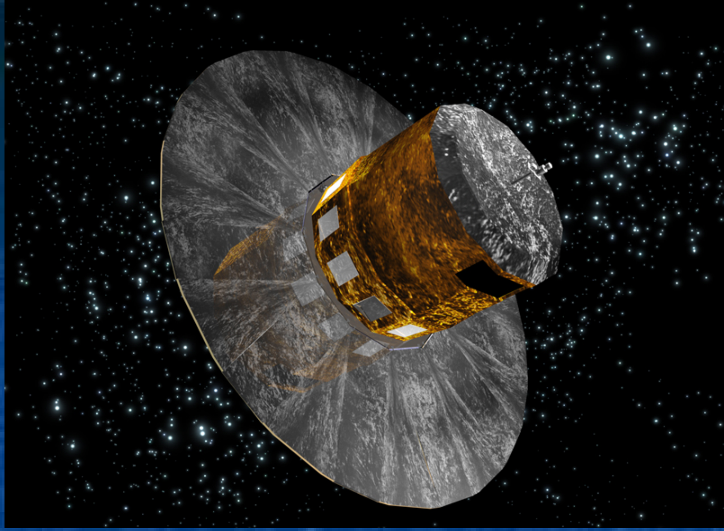

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Table 14: Magnitude-redshift relation for quasars in an area of 4000 square degrees. The table gives the expected number of quasars per magnitude and per interval of 0.5 in *z*, versus the central magnitude and redshift values (courtesy of D.P. Schneider).

	Magnitude									
Redshift	12	13	14	15	16	17	18	19	20	Total
0.25	4	8	10	12	113	1160	3355	238	0	4900
0.75	0	0	0	4	56	747	7013	16523	9481	33824
1.25	0	0	0	3	32	339	3646	16954	28430	49404
1.75	0	0	0	4	42	336	3019	13648	23667	40716
2.25	0	0	0	2	32	206	1709	8468	15948	26365
2.75	0	0	0	0	19	160	965	4651	8767	14562
3.25	0	0	0	0	9	63	364	1714	3579	5729
3.75	0	0	0	0	8	36	137	514	1207	1902
4.25	0	0	0	0	0	16	45	136	373	570
4.75	0	0	0	0	0	4	15	50	119	188
5.25	0	0	0	0	0	1	4	5	38	48
5.75	0	0	0	0	0	0	0	1	8	9
6.25	0	0	0	0	0	0	0	0	2	2
Total	4	8	10	25	311	3068	20272	62902	91619	178219

More on Gaia

- Gaia will detect quasars over 20,000 sq. degrees on the sky
- Multiply all these numbers by 5

More on Gaia (2)

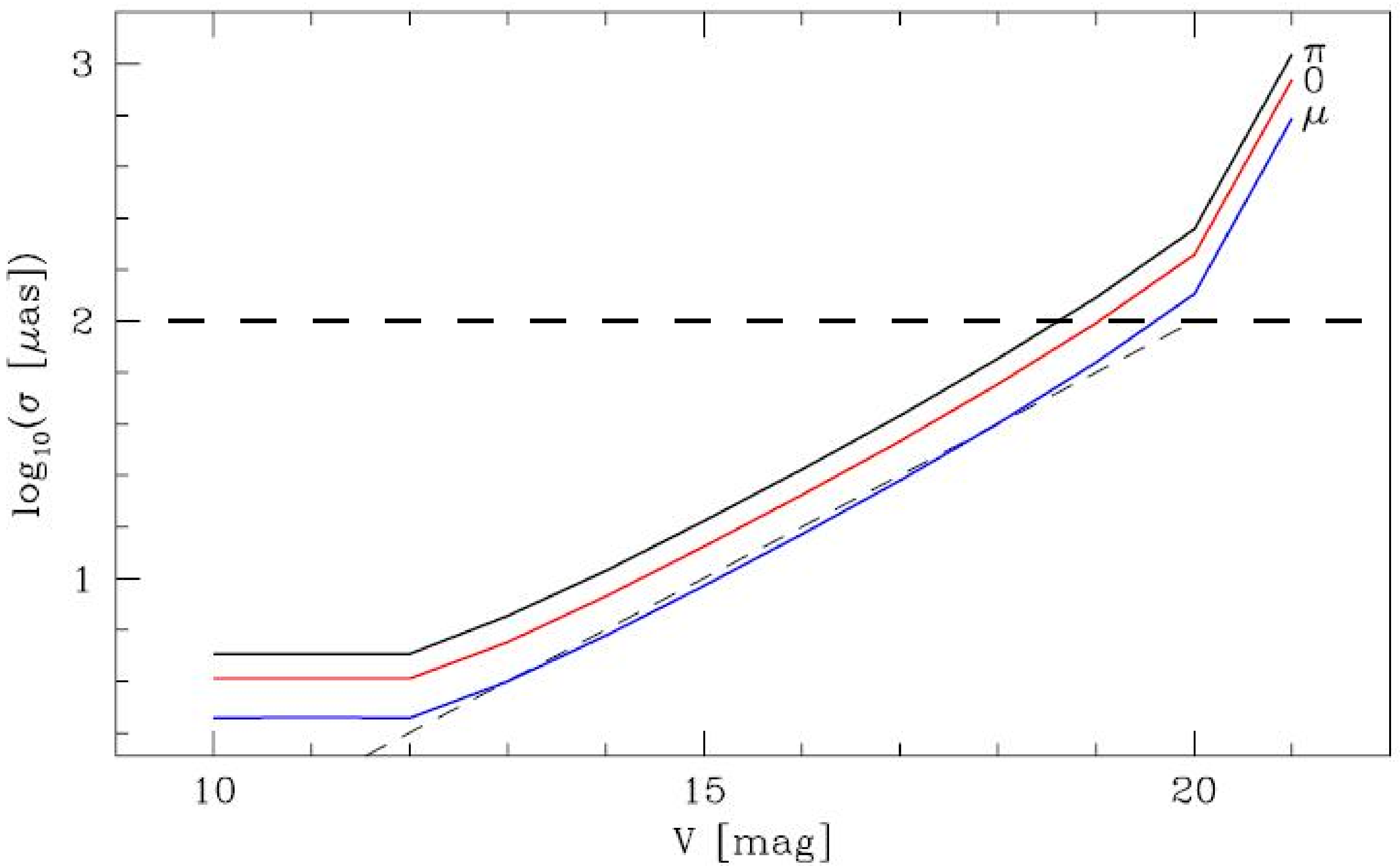
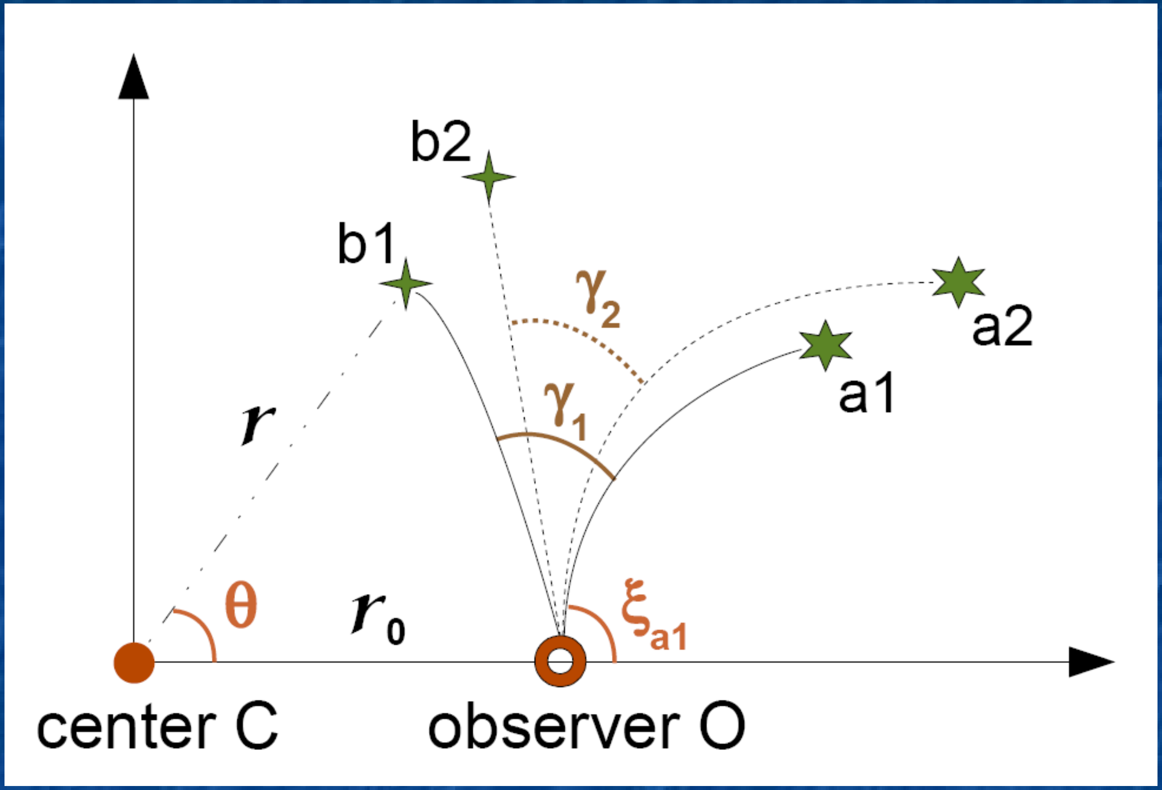


Figure 3. End-of-mission astrometric accuracy predictions, for the current Gaia-2 baseline design, as a function of V magnitude for an unreddened solar-type star (spectral type G2V). The dashed line refers to the top-level mission requirement, i.e., $\sigma = 10\ \mu as$ at $V = 15$ mag, extrapolated to other magnitudes assuming centroiding accuracies are photon-noise limited.

The Cosmic Parallax effect



- In a FRW metric, $\Delta_t\gamma \equiv \gamma_2 - \gamma_1 = 0$.
- In any anisotropic metric, however, $\Delta_t\gamma \neq 0$, and we have cosmic parallax.

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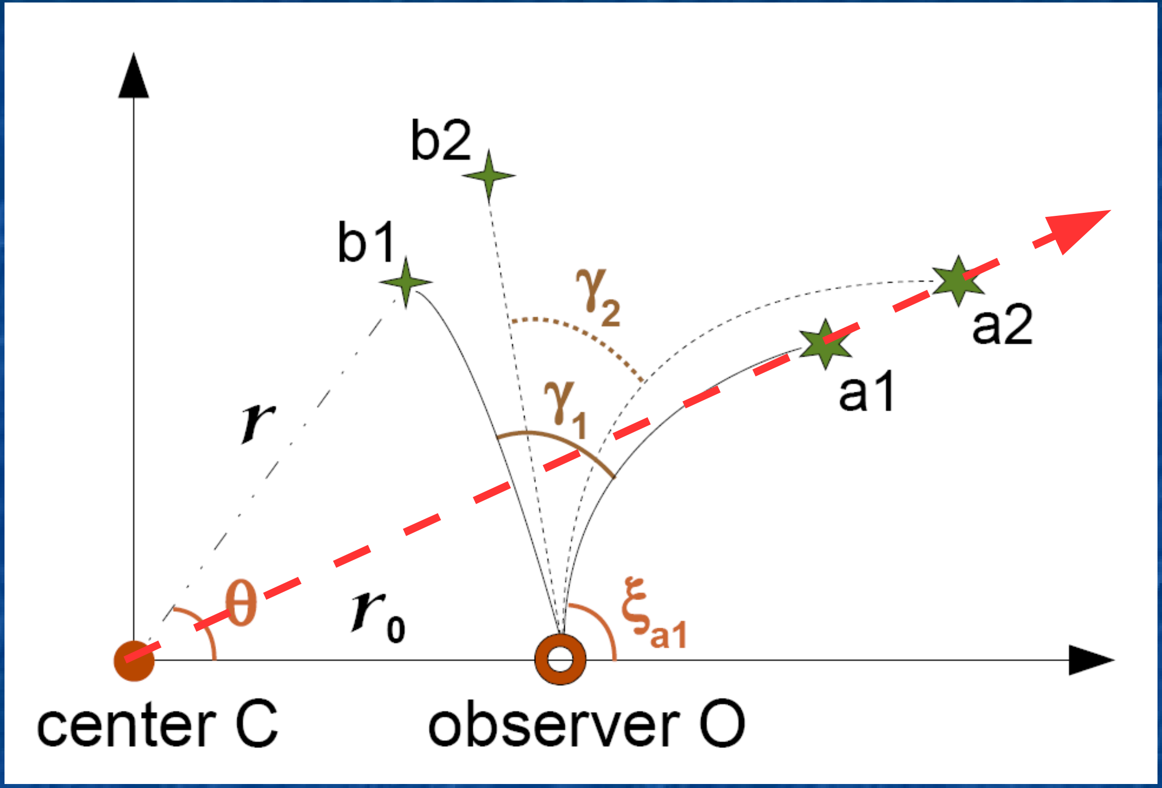

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Estimating the Cosmic Parallax

- 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 at same z initially separated by $\Delta\theta$.

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

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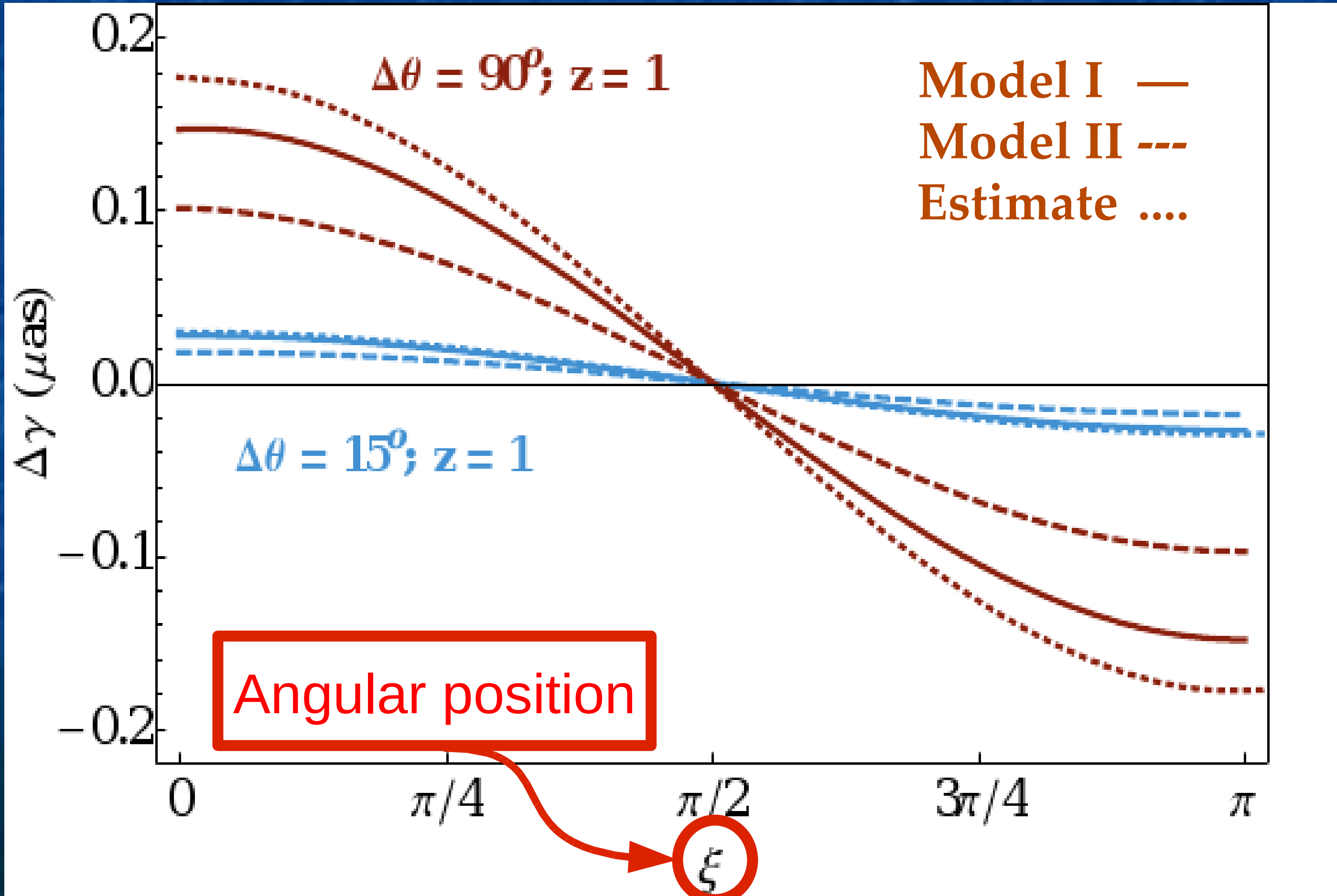
distance to the void center

"physical" distance

dipole effect

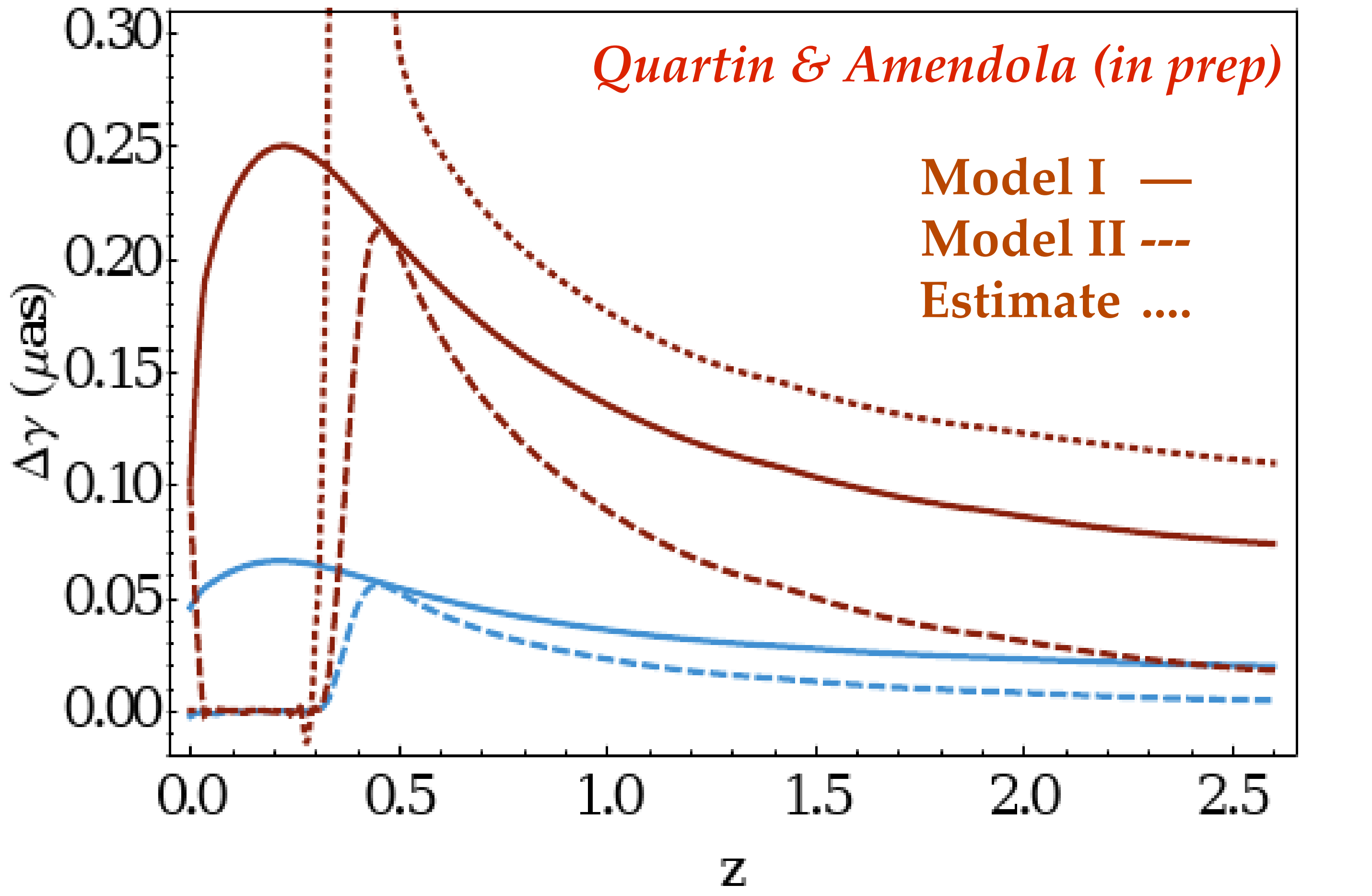
Results

- 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)



Results (2)

- $\Delta_t\gamma$ in 10 years for a pair of quasars separated by 90° (also typical), at different redshifts



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 (PRD)
astro-ph/0610331 (PRD)

- 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)

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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

Cosmic Parallax in other models

- The cosmic parallax effect is sensitive to any kind of anisotropy;
- Measurement of late-time anisotropy!
- Primordial anisotropy gets diluted with expansion
  - Present anisotropy → anisotropic pressure field!
- Overall effect can be much higher in Bianchi I
- Different anisotropic models → different multipole dependence;

Koivisto & Mota
arXiv:0707.0279 (ApJ)
arXiv:0801.3676 (JCAP)

Bianchi I

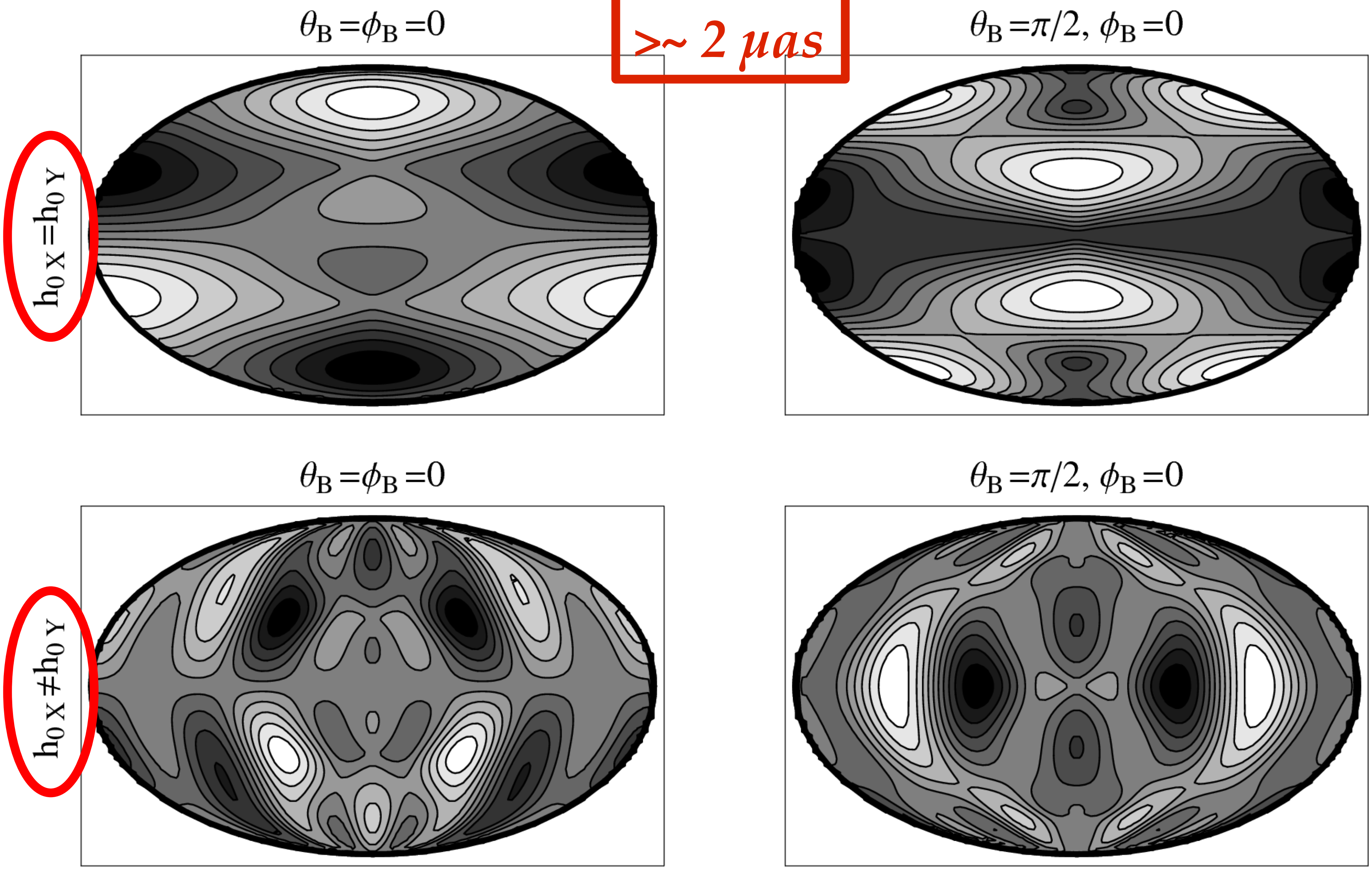
- Bianchi I metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{d}x^2 + b^2(t)\mathrm{d}y^2 + c^2(t)\mathrm{d}z^2$$

  - Flat, no overall vorticity
  - Non-zero shear $\Sigma_x \equiv \frac{H_x}{H} - 1 \neq 0$

$$H \equiv \frac{1}{abc}\frac{\mathrm{d}}{\mathrm{d}t}(abc)$$

Cosmic Parallax in Bianchi I



Quercellini, Cabella, Amendola, Quartin & Balbi 0905.4853

Real-Time Cosmology

- Cosmic parallax is but one of the recently proposed Real-Time Cosmology observable effects.

	radial	transverse
global *(velocity)*	Sandage-Loeb effect	cosmic parallax
local *(acceleration)*	peculiar acceleration	proper acceleration

Quartin, Amendola, Balbi & Quercellini (in prep)

Real-Time Cosmology (2)

	radial	transverse
global *(velocity)*	Sandage-Loeb effect	cosmic parallax
local *(acceleration)*	peculiar acceleration	proper acceleration

- S-L effect → measure dz/dt → as many objects as possible

  Uzan, Clark & Ellis, 0801.0068 (PRL)

- Pecul. accel. → measure accel. of stars inside Milky Way → e.g. distinguish between Newton or MoND

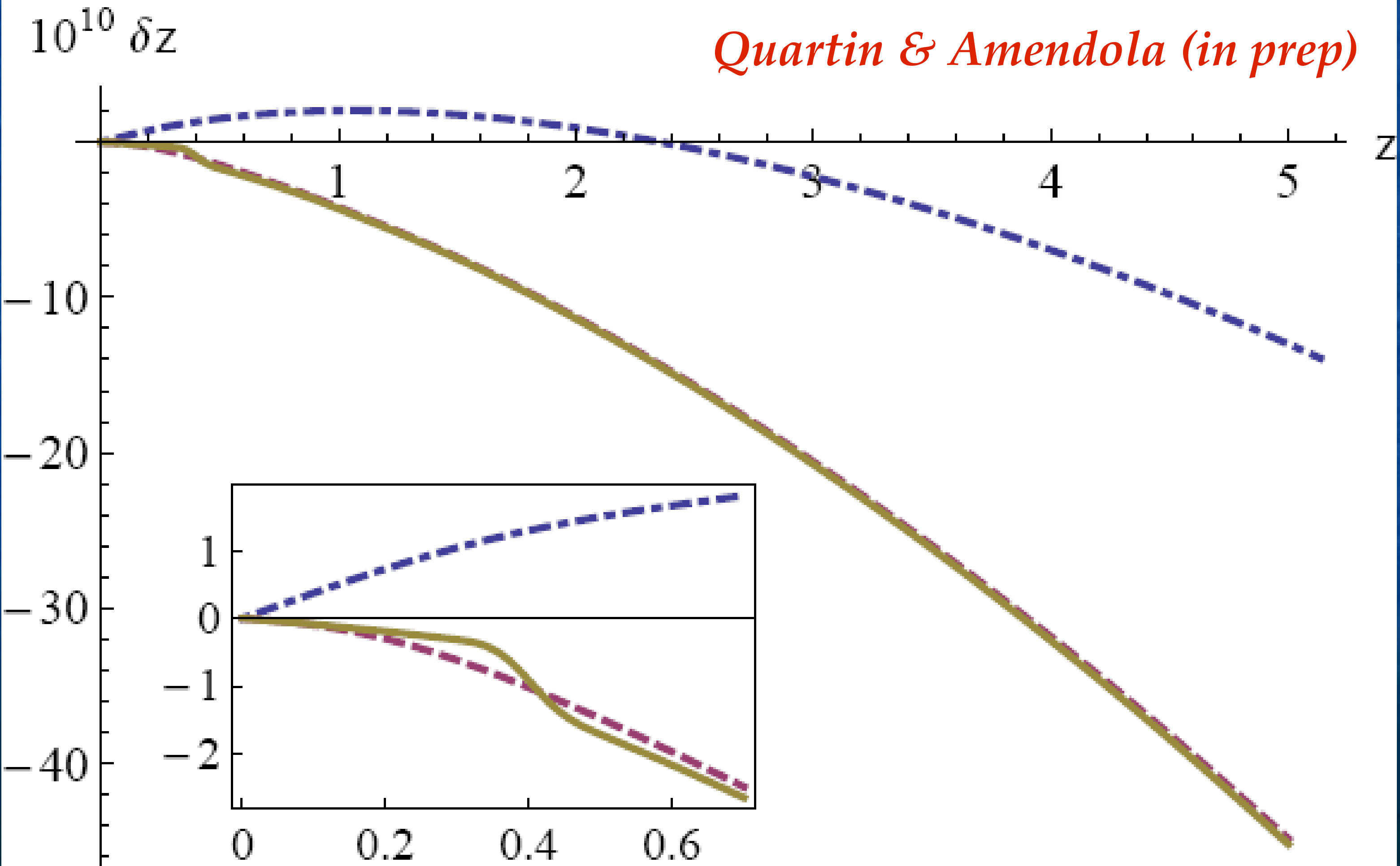
  Amendola, Quercellini & Balbi 0708.1132 (Phys.Lett.B)

- Proper accel. → measure dz/dt → objects in a cluster → independent measure of mass (no need to assume virialization)

  Quartin , Amendola, Balbi & Quercellini (in prep)

Redshift Drift in LTB

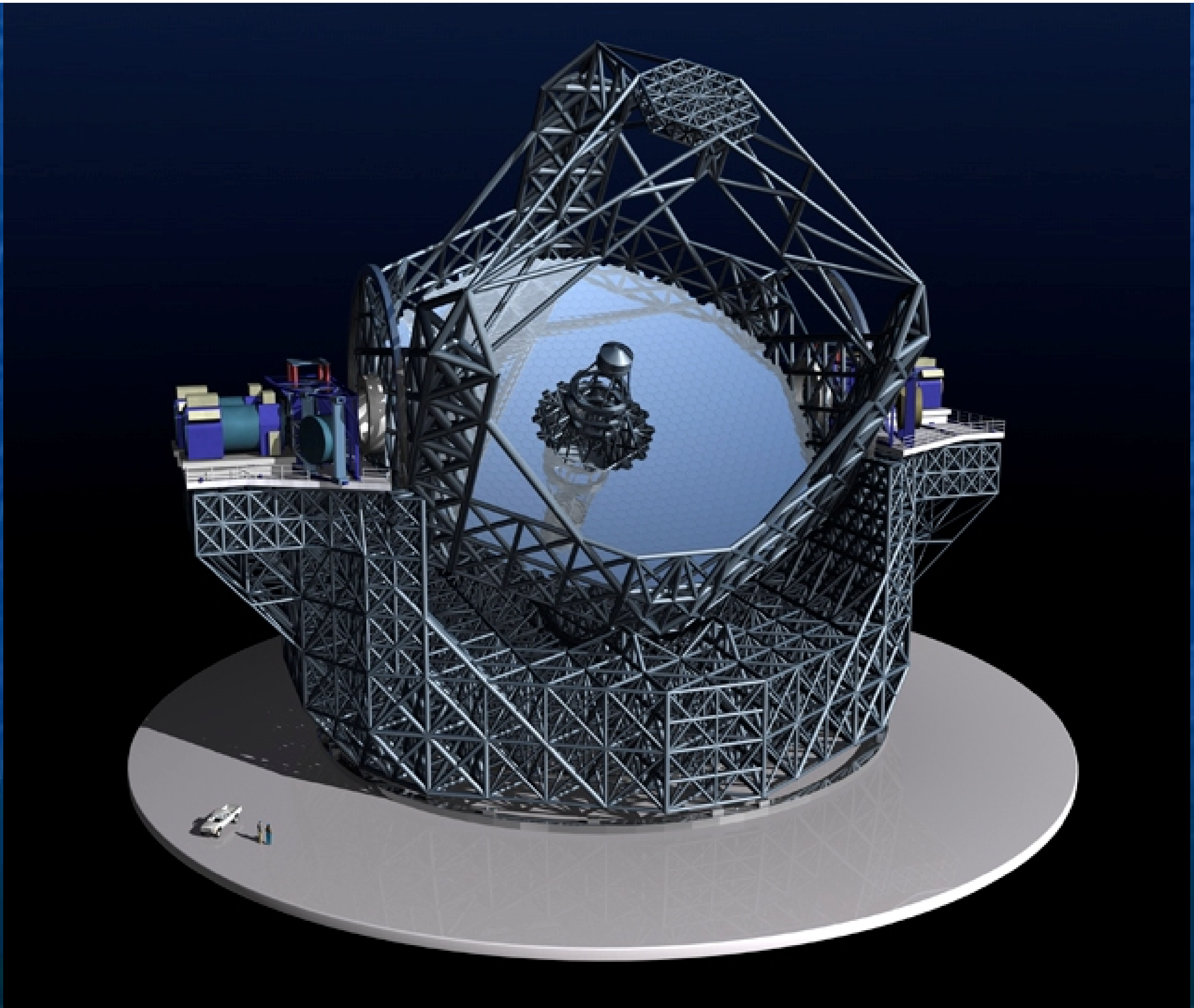
- Sandage-Loeb redshift drift in LTB is different from ΛCDM!



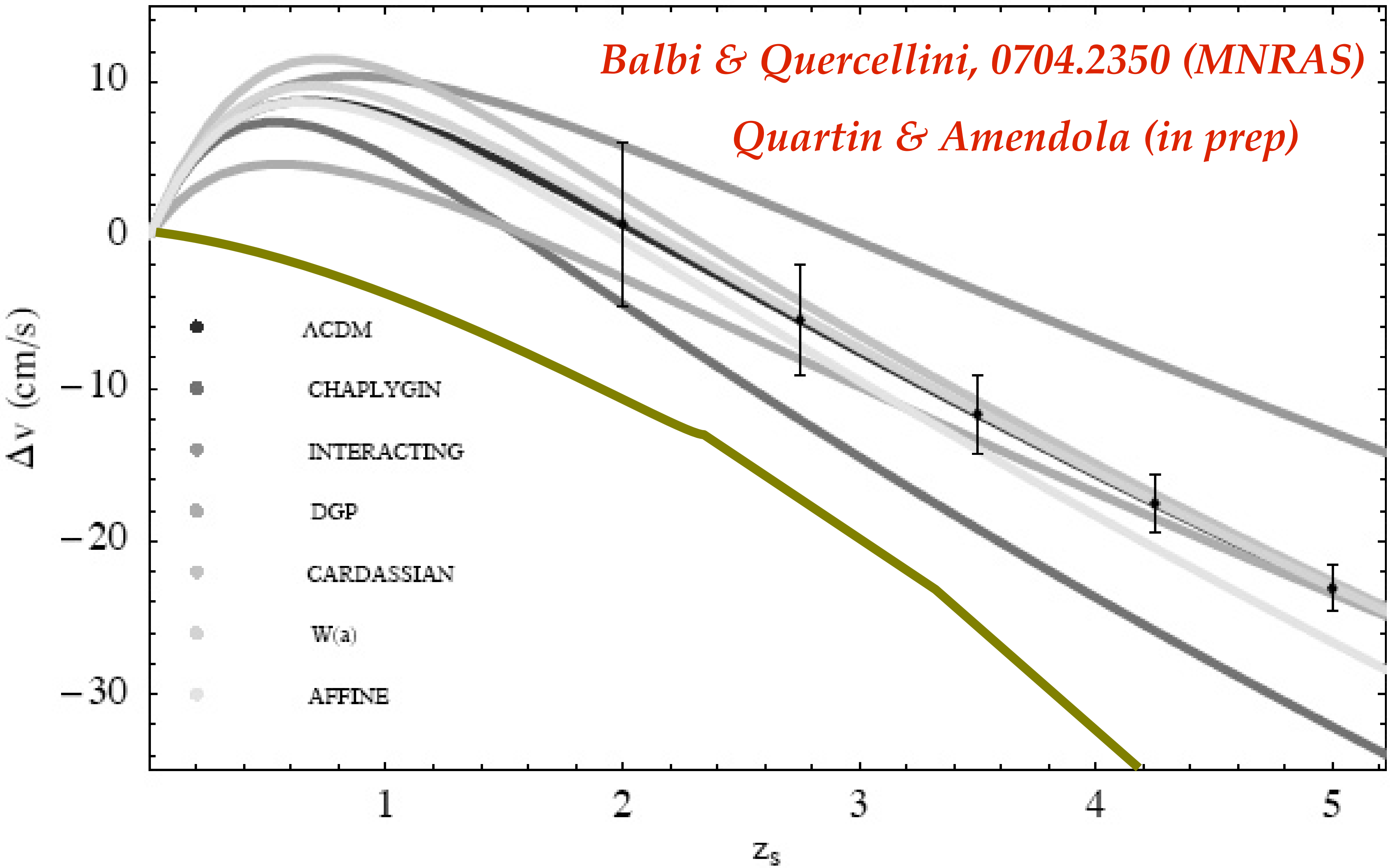
The Extremely Large Telescope

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.



z Drift in other DE models



Conclusions

- *"Cosmic parallax"* is not a regular parallax!
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- *"Cosmic parallax"* is not a regular parallax!
- Competitive consistency test of FRW metric;
- LTB is less symmetric than FLRW
  - FLRW less symmetric than static universe
- Anisotropy test $\rightarrow$ measures present anisotropy;
- It's within observational reach of Gaia;

Conclusions (2)

- Advantages over other anisotropy probes
  - CMB dipole:
    - already limited by cosmic variance
    - completely degenerated with our peculiar velocity
  - Other CMB multipoles:
    - assume anisotropy is not growing
  - Supernovae:
    - Need > 10,000 SNe for same sensitivity of Gaia
- Requires good subtraction of aberration changes in case of void models.

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Thanks!

LTB models (4)

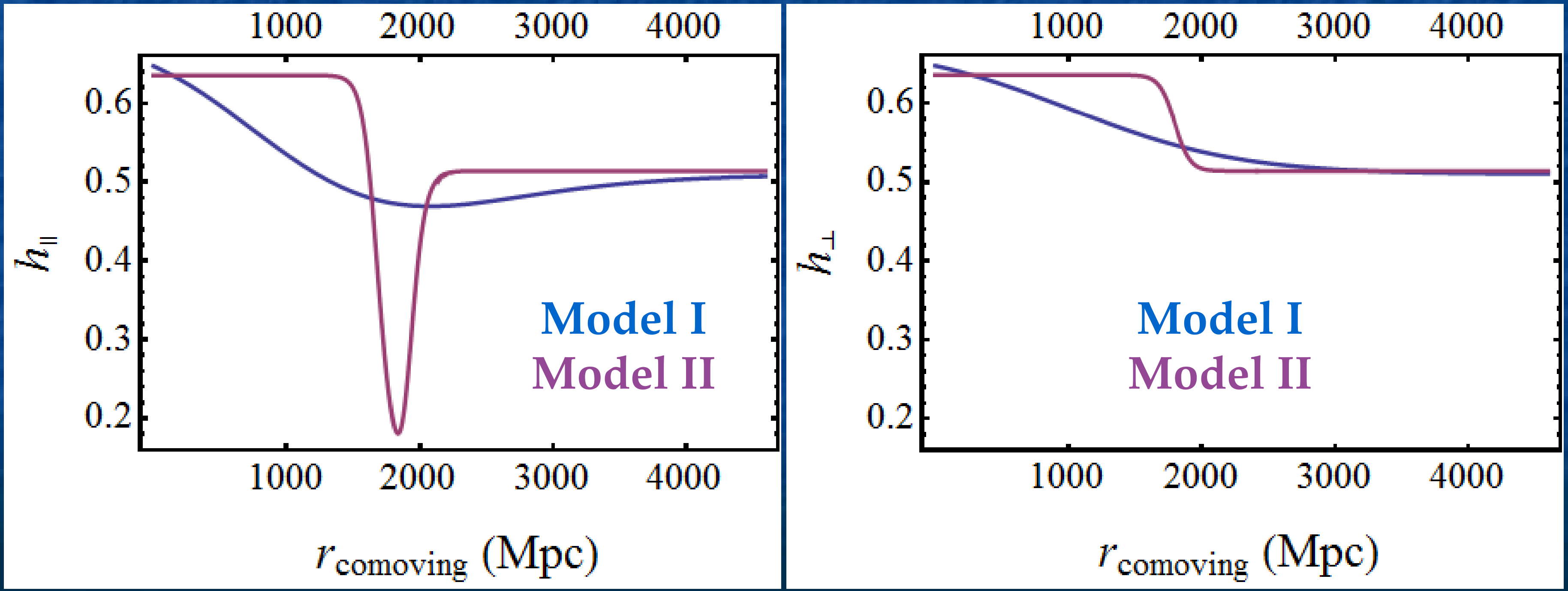
$$R' \equiv \frac{\partial R}{\partial r}$$

- Hubble parameter is no longer unique

$$H_{||} = \frac{1}{R'}\frac{\partial R'}{\partial t}$$

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

$$H_{\perp} = \frac{1}{R}\frac{\partial R}{\partial t}$$



Distinctions between $H_{||}$ and $H_{\perp}$

- Baryon Acoustic Oscillation signal depends partly on $H_{||}$
- SNe observations are only related to $H_{\perp}$

$$q(z) = -1 + \frac{d \ln H_{||}(z)}{d \ln(1+z)}$$

$$w(z) \equiv \frac{p(z)}{\rho(z)} = -1 + \frac{1}{3} \frac{d \ln \left[\frac{H_{\perp}^2(z)}{H_0^2(r)} - \Omega_M(r)(1+z)^3 \right]}{d \ln(1+z)}$$

García-Bellido & Haugbolle: 0802.1523 (JCAP)

Other Gaia Goals

- Stellar parallax → distances without physical assumptions.
- Faintest objects → a more complete view of the stellar luminosity function.
- Large amount of objects → examine the more rapid stages of stellar evolution. Also important → understand the dynamics of our galaxy: 1 billion stars = 1% of its content.
- Astrometric and kinematic properties of star → understand the various stellar populations, especially the most distant.
- Tangential speeds of 40 million stars to a precision of better than 0.5 km/s

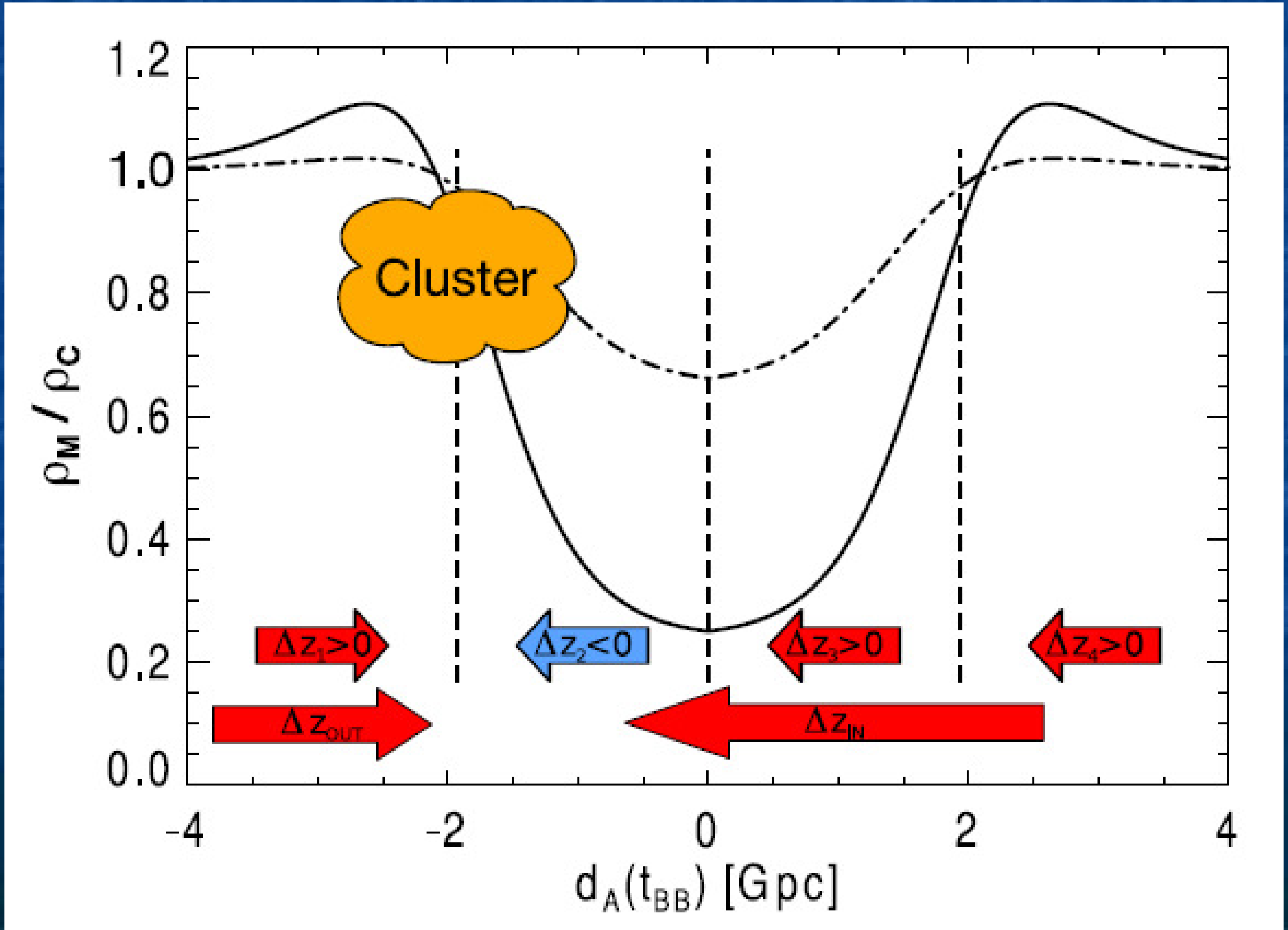
More on Gaia (3)

Table 1. Target accuracies in parallax (σ_π), position (at mid-epoch, σ_0) and proper motion (σ_μ), versus G magnitude. The values are sky averages.

G (mag)	10	11	12	13	14	15	16	17	18	19	20	21
σ_π (μas)	4	4	4	5	7	11	17	27	45	80	160	500
σ_0 (μas)	3	3	3	4	6	9	15	23	39	70	140	440
σ_μ (μas yr^{-1})	3	3	3	4	5	8	13	20	34	60	120	380

Extras: Constraints on Void Models

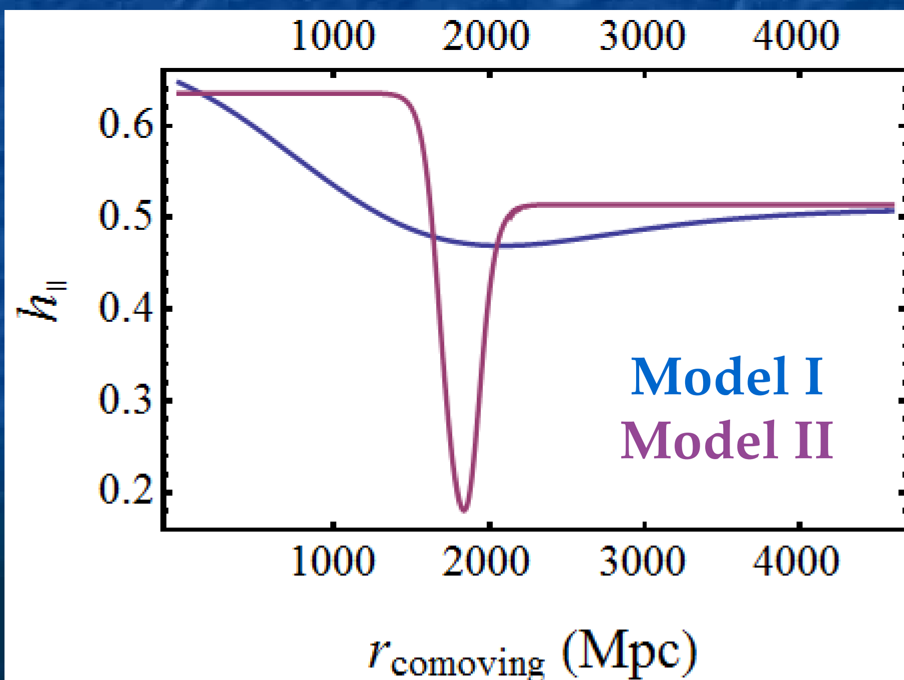
- Kinematic Sunyaev-Zeldovich effect from large clusters
  - *García-Bellido & Haugbolle: 0807.1326 (JCAP)*



Estimating the Cosmic Parallax (2)

$$\Delta_t \gamma \simeq \Delta t \underbrace{\left(\overline{H}_{\mathrm{obs}} - \overline{H}_X\right)}_{\text{ZERO inside the void in Model II}} \frac{X_0}{X}\left(\cos\theta\,\Delta\theta + \sin\theta\,\cancel{\frac{\Delta X}{X}}\right)$$

Dipole effect



$$\boxed{\overline{H_X} \simeq H^{\mathrm{out}}_{||,0}}$$

Gaia Forecast