E pur si muove!
Detecting our acceleration through space

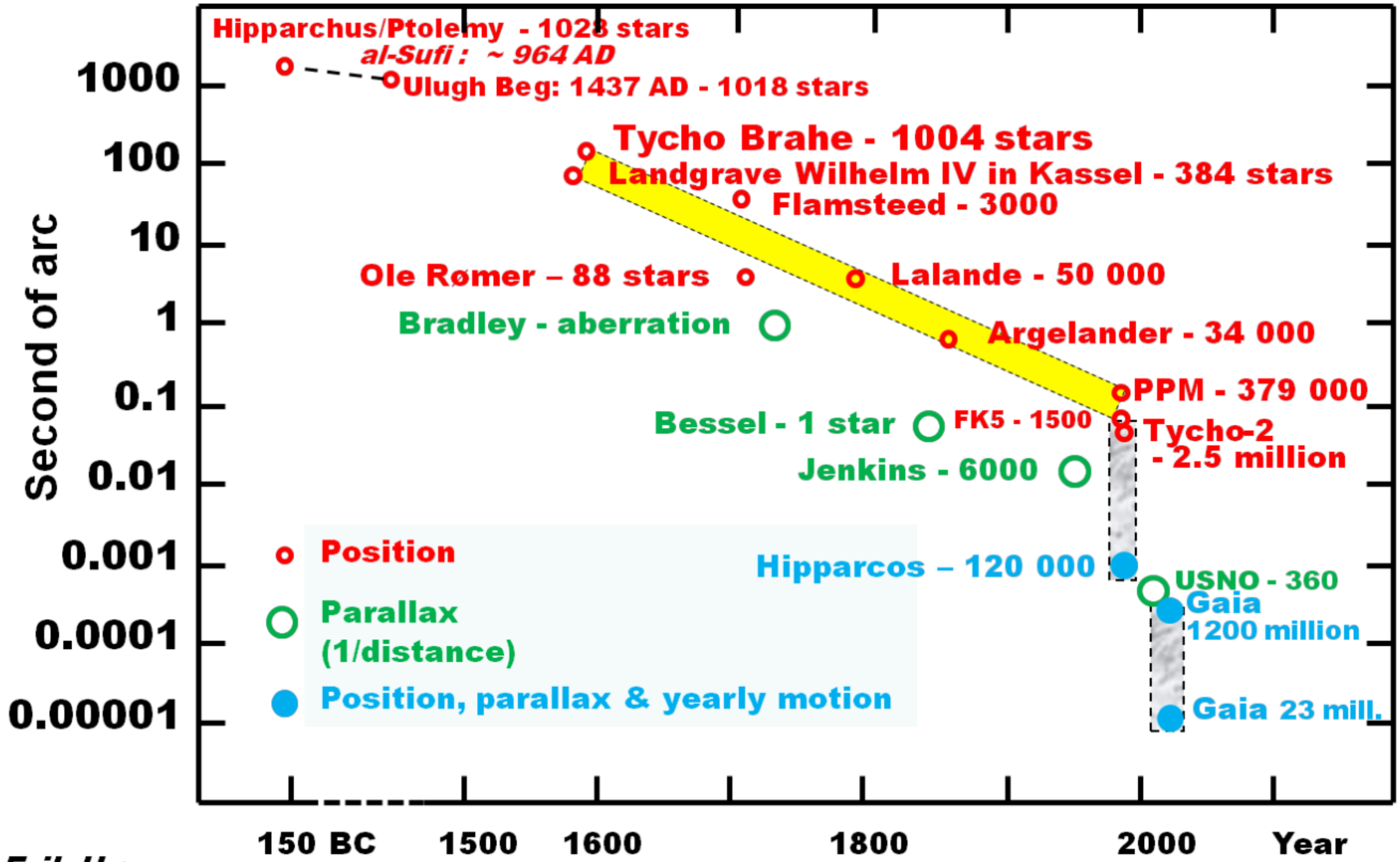
Christian Marinoni

Centre de Physique Théorique
Aix-Marseille Université

Bel & Marinoni 2018 PRL 121.021101

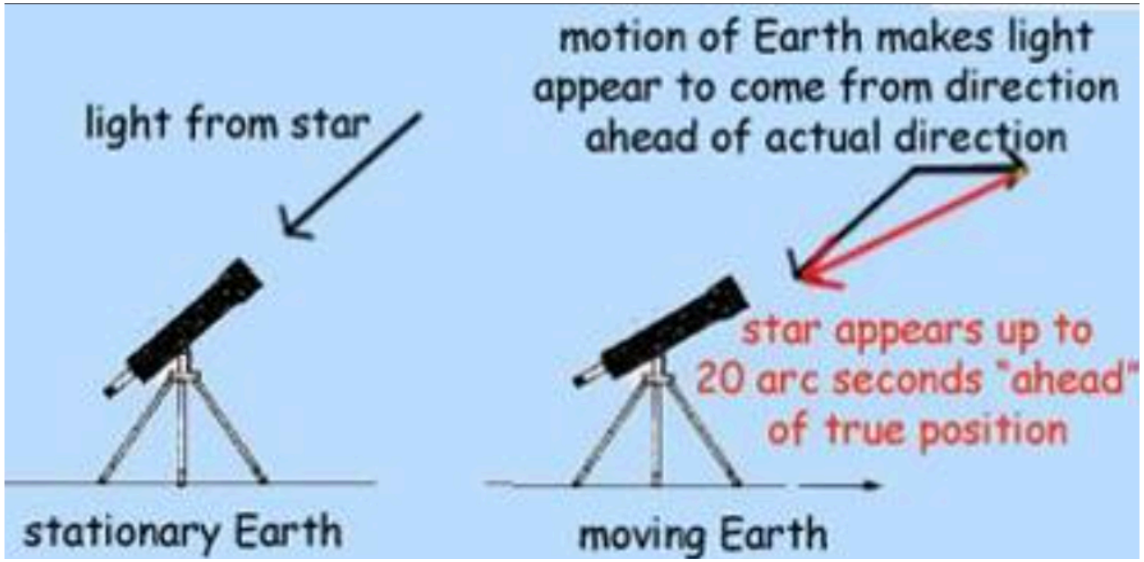
Colloque Nationale Dark Energy   Paris 24/10/2018

Astrometric Accuracy during 2000 Years



Erik Høg
1995/2016

Aberration of light



$$\theta \approx \beta = \frac{v}{c}$$

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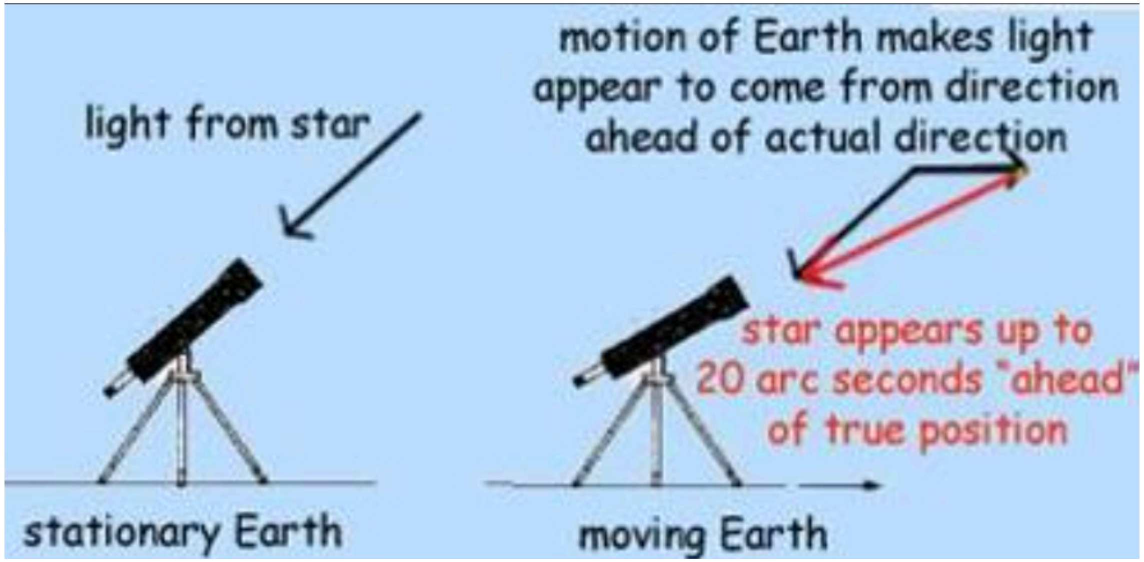


$$\theta \approx \beta = \frac{v}{c}$$

Cosmological Aberration Drift:

On dimensional grounds $\dot{\theta} = \dot{\beta} \approx H\beta$

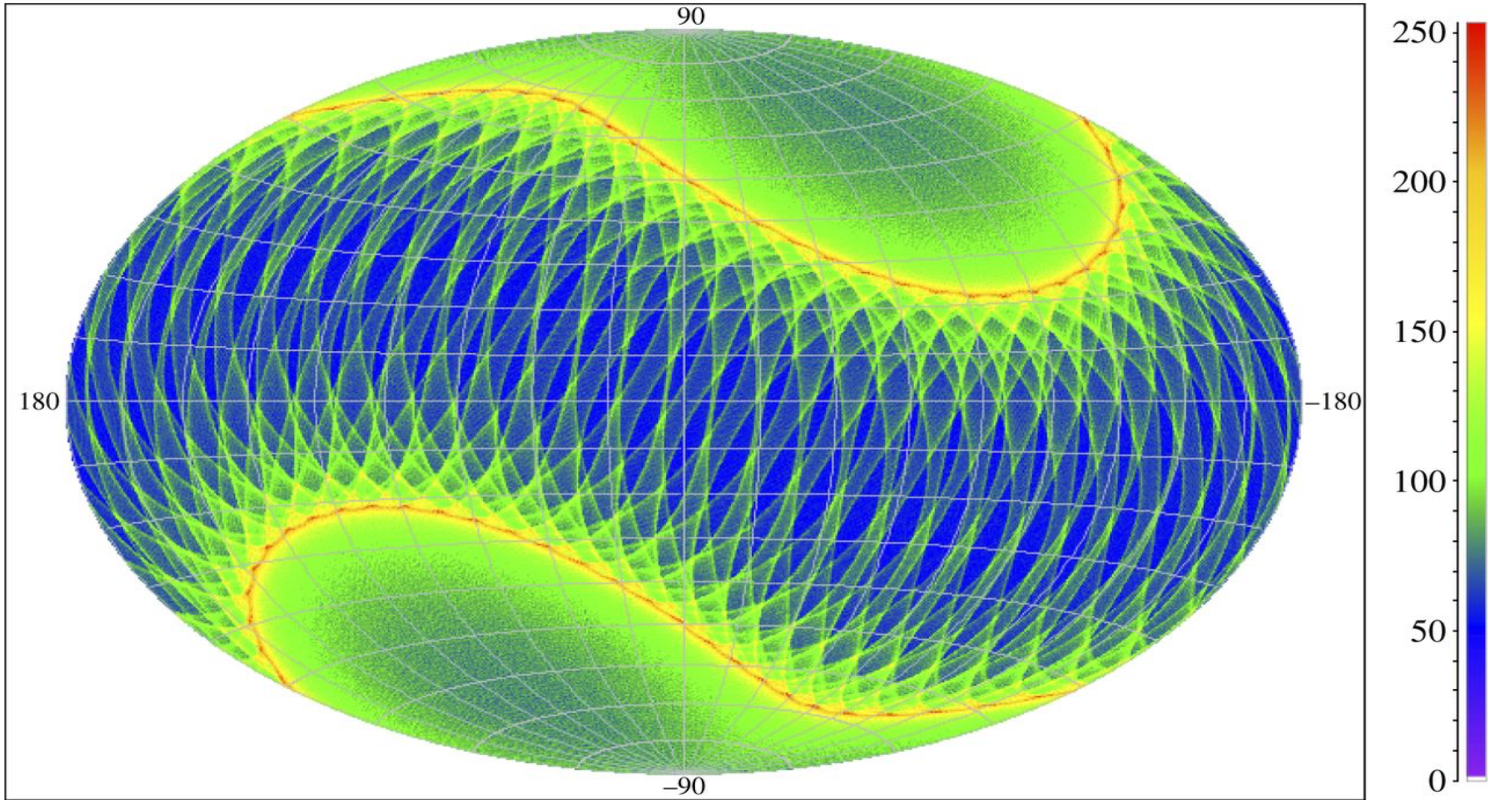
$\beta_{LG/CMB} \sim 630c^{-1}km/s \quad \Rightarrow \quad \mathrm{d}\theta \sim 0.4$ (μas/10yrs) for each source!

gaia

ESA Astrometric Space Mission

$$1 < \sigma / \mu as < 200$$

Gaia field transits (ICRS) for 5 years



- All sky field
- Multiple pass strategy → time lag

~ 5*10^{5} QSO

For a 3000 km maximum baseline the angular resolution is

$$\theta = \frac{20}{\nu_{\rm GHz}}\ {\rm mas} = 2\ {\rm mas\ at\ 10\ GHz.} \quad (3.1)$$

At 10 GHz the SKA will achieve a minimum detectable flux density of 0.3 μJy (5σ) in one hour. The SKA will be designed for high dynamic range imaging (see Table 1). At this frequency the imaging dynamic range will be less challenging than lower frequency so noise-limited images over the full field-of-view will be routine. The angular precision of phase-referenced astrometry is given approximately by

$$\Delta\theta = \frac{\theta}{\rm SNR}, \quad (3.2)$$

where SNR is the signal-to-noise ratio on the radio source. In a deep VLA integration at 8.4 GHz by Fomalont et. al. (2002), 0.64 sources per arcmin^2 were detected above 7.5 μJy. From fits to the number of sources versus flux density they derive an expression for the integral source counts,

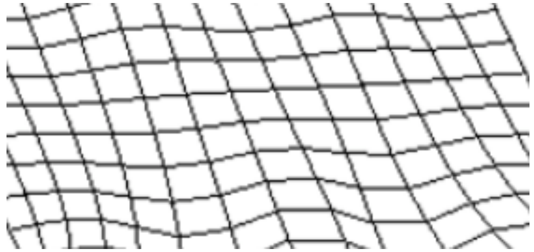
$$N(>S) = 0.099(\frac{S}{40})^{-1.11}. \quad (3.3)$$

The SKA will achieve SNR > 2000 in one hour at 10 GHz on sources with flux density above 200 μJy. Within one square degree there will be on average 105 sources above this flux limit. The astrometric precision for these source will be $\sim$1 μas. In the same area there will be more than 1000 source above 12 μJy which will have differential astrometry to $\sim$10 μas. The SKA could therefore very quickly establish a dense grid of more than 10,000,000 sources with astrometric accuracy of a few μas that can be re-observed at multiple epochs.

Taylor A.R. IAU 2013

Cosmological Aberration Drift

$$ds^2 = e^{2\Phi}dt^2 - a^2(t)e^{-2\Psi}\delta_{ij}dx^i dx^j$$



An observer S′, in (time-like) geodesic motion has four-velocity

$$\frac{dx^\mu}{d\tau} = \gamma e^{-\Phi}\left(1, \vec{v}_p\right)$$

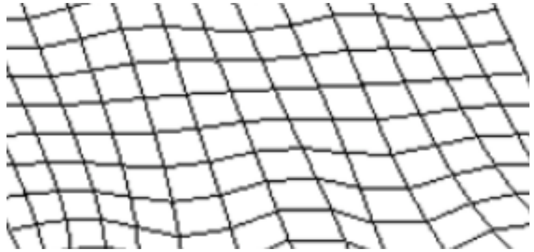
$$\tan\,\theta' = \frac{\sin\theta}{\gamma(\beta + \cos\theta)}$$

$$\gamma = (1 - \beta^2)^{-1/2}$$

$$\vec{\beta} = e^{-(\Phi+\Psi)}a\vec{v}_p$$

Comoving Peculiar Velocity $\vec{v}_p$

Cosmological Aberration Drift



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$$\frac{d\theta'}{d\tau} = \gamma \mathring{\theta}' = \cos^2\theta' \frac{-\sin\theta \left[\mathring{\beta} + \mathring{\gamma}\gamma^{-1}(\beta + \cos\theta)\right] + \mathring{\theta}(1 + \beta\cos\theta)}{[\cos\theta + \beta]^2}$$

$$\circ \equiv e^{-\Phi} \frac{d}{dt}$$

$$\frac{d\theta'}{dt} \approx -\sin\theta'\ \dot{\beta} + \dot{\theta}$$

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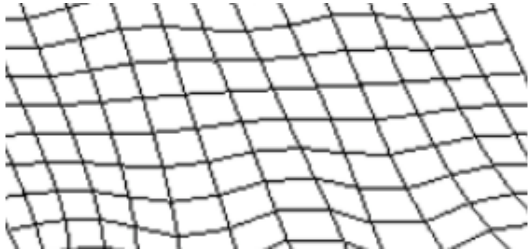

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Cosmological component of the Aberration Drift

Acceleration given by geodesic equations

$$\mathring{\boldsymbol{\beta}} = -\mathcal{H}\boldsymbol{\beta}(1-\beta^2) - \left[\nabla\Phi - 2\boldsymbol{\beta}\cdot\nabla(\Phi+\Psi)\boldsymbol{\beta} + \beta^2\nabla\Psi\right]$$

$$\circ \equiv e^{-\Phi}\frac{d}{dt} \qquad \nabla \equiv a^{-1}e^{\Psi}\frac{\partial}{\partial \mathbf{x}} \qquad \mathcal{H} \equiv e^{-\Phi}(H-\dot{\Psi})$$

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Gravitational Potential given by linear EFE

$$\nabla\Phi \propto \vec{\beta}$$

Large scales
Neglect decaying and rotational modes

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Neglect decaying and rotational modes

$$\dot{\vec{\beta}} = -H\vec{\beta}\left(1 - \frac{3\Omega_m \mu}{2f}\right)$$

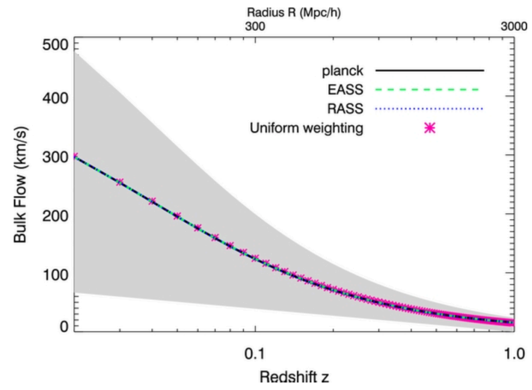
Two competing effetcts: gravitational pull and expansion drag

$$f = d\ln\delta / d\ln a$$

$\dot{\vec{\beta}}$ of what with respect to what?

The RF w/r to which acceleration is measured:

Comoving frame defined by distant galaxies



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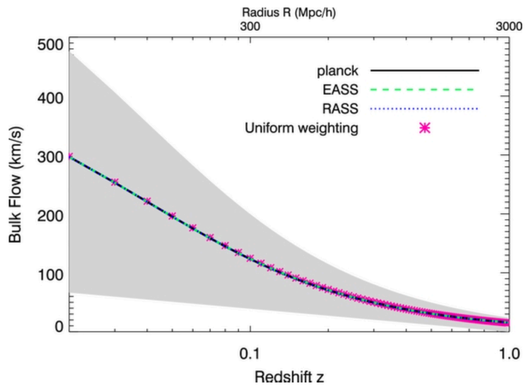

The RF w/r to which acceleration is measured:

Comoving frame defined by distant galaxies

We assume that it is the centroid of the Local Group of galaxies (LG) that moves and accelerates with respect to the CF according to the linear formula

$$\dot{\vec{\beta}}_{LG/CF} = -H\vec{\beta}_{LG/CF}\left(1-\frac{3\Omega_m\mu}{2f}\right)$$

- CAD Signal! If QF ~ CMB frame, then high velocity (β~630km/s) favors the signal !

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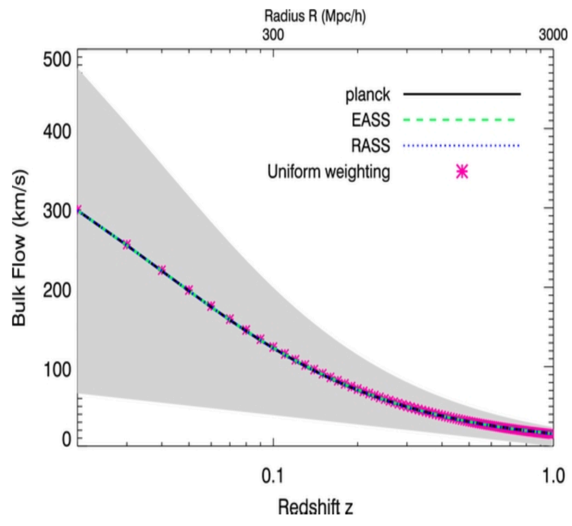

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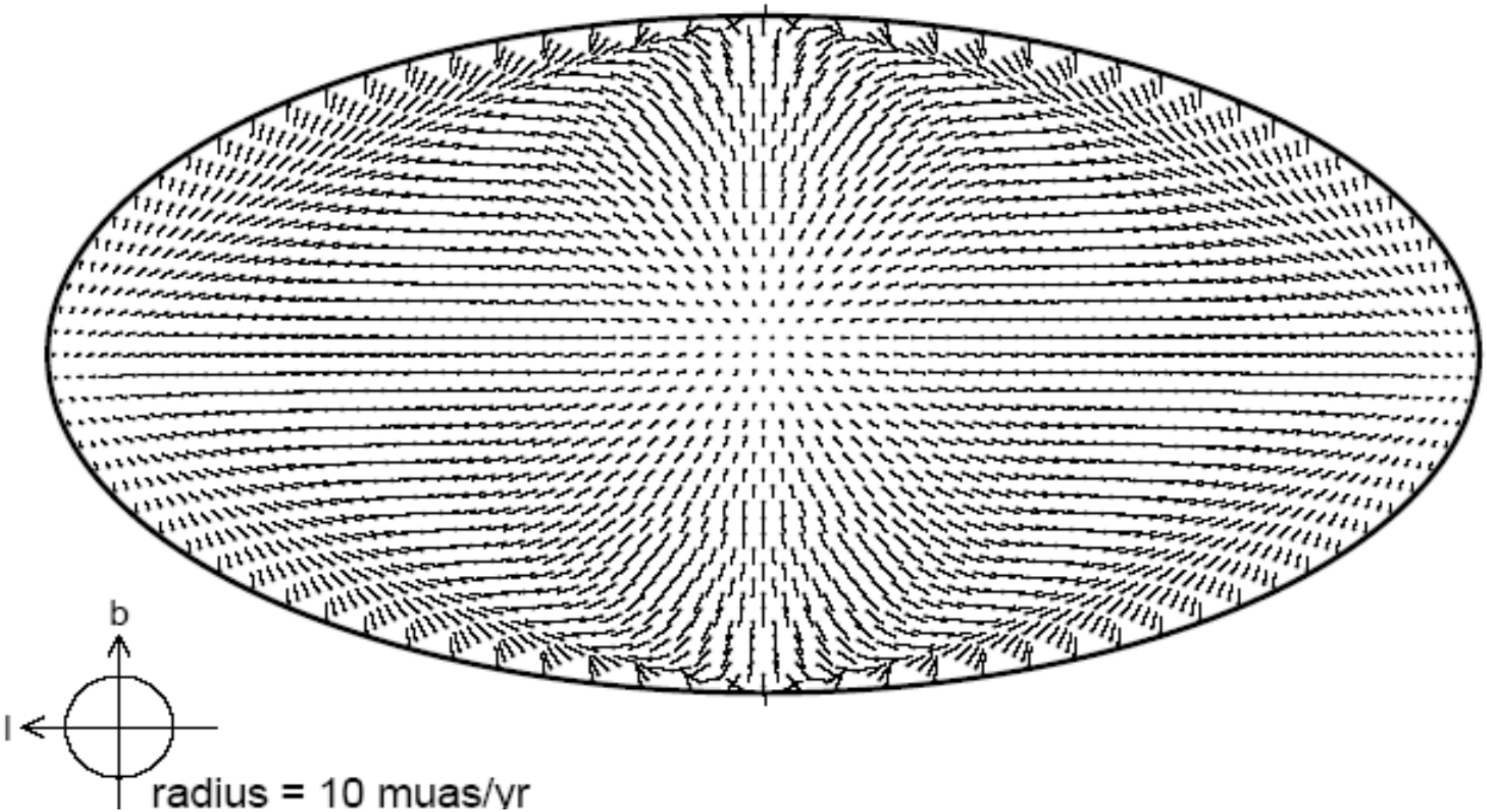
$$\dot{\vec{\beta}}_{LG/CF} = \dot{\vec{\beta}}_{Earth/CF} - (\dot{\vec{\beta}}_{Earth/Sun} + \dot{\vec{\beta}}_{Sun/MW} + \dot{\vec{\beta}}_{MW/LG})$$

- CAD Signal! If CF ~ CMB frame, then high velocity (β~630km/s) favors the signal !
- Just one of the non inertial signatures that must be subracted

Motion of the Sun around the MW Center $\beta_{Sun/MWC}$



Kovalewsky 2003

This effects reaches 4 μas per year in some Sky directions.

Detected by studying apparent streaming motion of QSO towards the center of the MW by Titov et al (2011)

Motion of the MW with respect to the LG Center $\beta_{MW/LG}$

The Local Group is a galaxy overdensity that decoupled from the cosmological expansion and is now a gravitationally bound system.

Fully non-linear (Newtonian) spherical collapse model

- LG Mass is essentially provided by Andromeda (largest structure in LG)
- Relative velocity (132 km/s) aligned with the separation vector (<10 deg)

$$\dot{\vec{\beta}}_{MW/LGC} = -H\left(\vec{\beta}_{MW/LGC} + \frac{\Omega_{m0}}{2}\left(1+\delta_r\right)H_0\vec{r}\right)$$

$$\dot{\vec{\beta}}_{MW/LGC} = H(3 \pm 30 km/s)\hat{r}$$

One order of magnitude smaller then the effect we are trying to estimate!

Testing the linear relation $\nabla\Phi = -\frac{3\Omega_m}{2f} H\vec{\beta}$ for LG-like environments

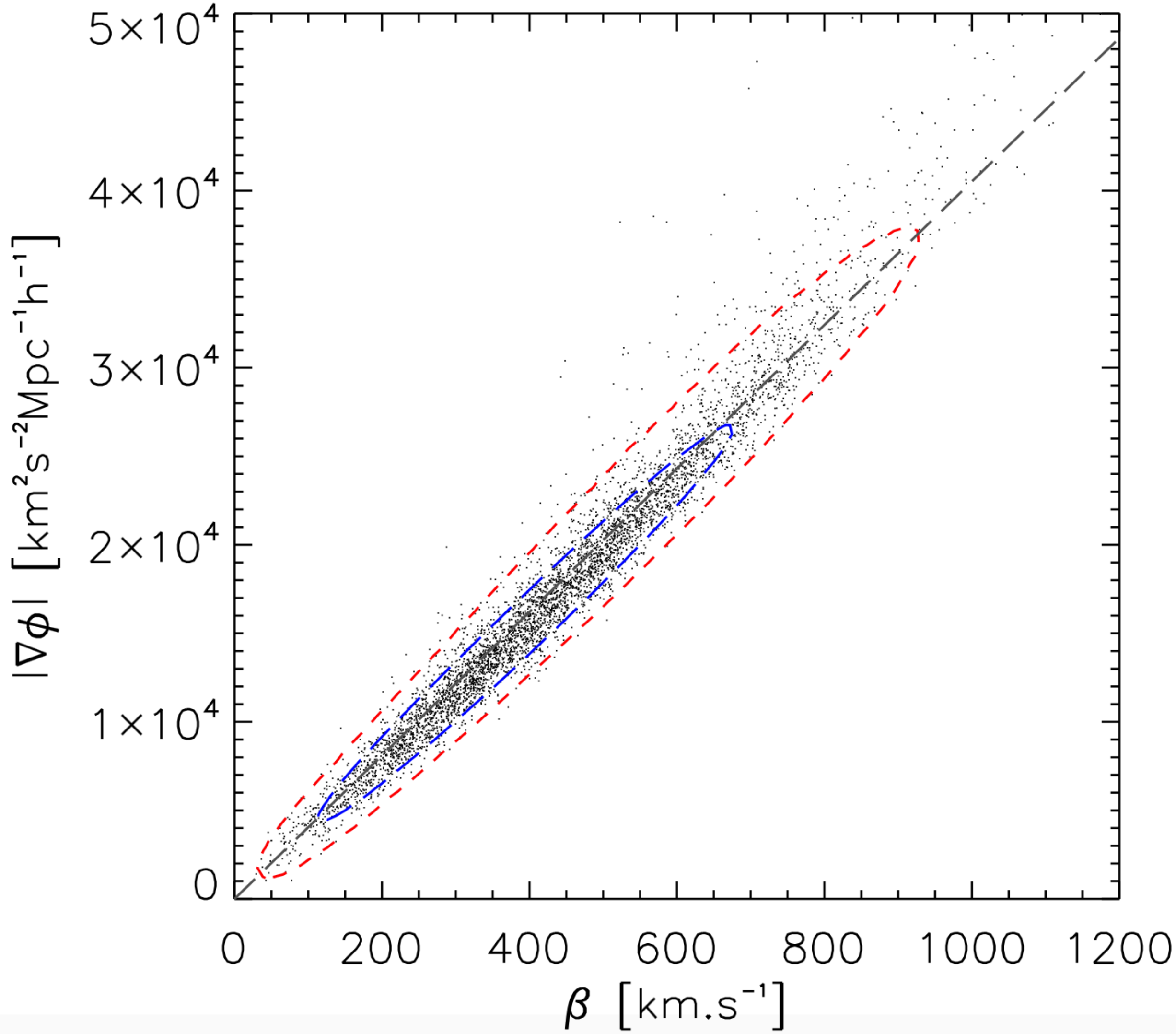
DEMNUni simulations
L=2Gpc/h
$N=2048^3$
$M=8*10^{10}\ M_{sun}/h$
Carbone et al 2015

We define LG-like environments by (top-hat) smoothing the particle distribution of the N-body simulation on a scale $R = 3h^{-1}Mpc$
Tully et al 2014

Typical overdensity is

$$0 < \delta < 0.5$$

Gonzalez et al 2013
Maccio' et al 2015



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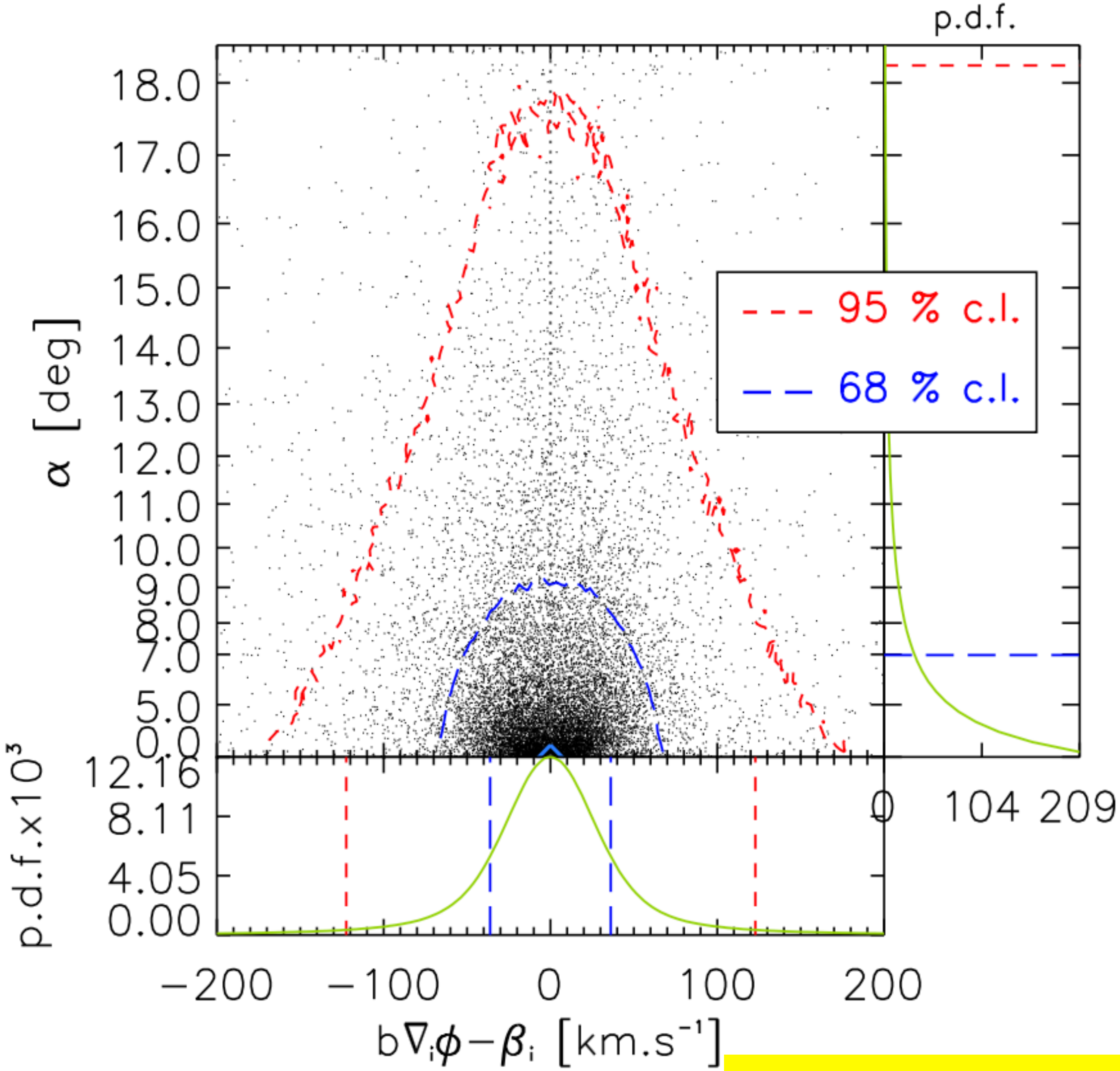
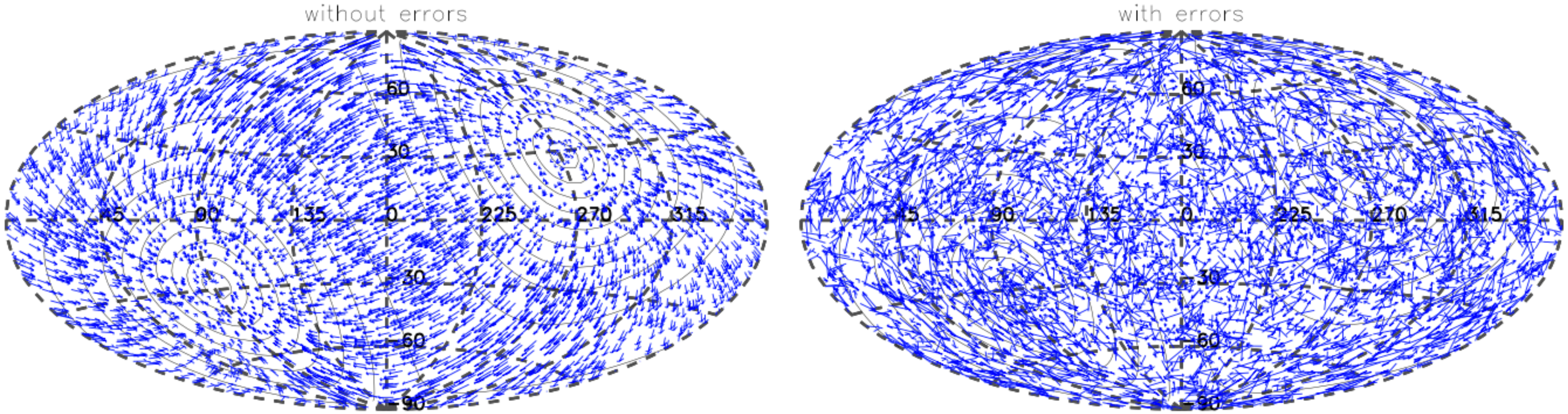


$\delta\theta < 9^\circ$ (68%)

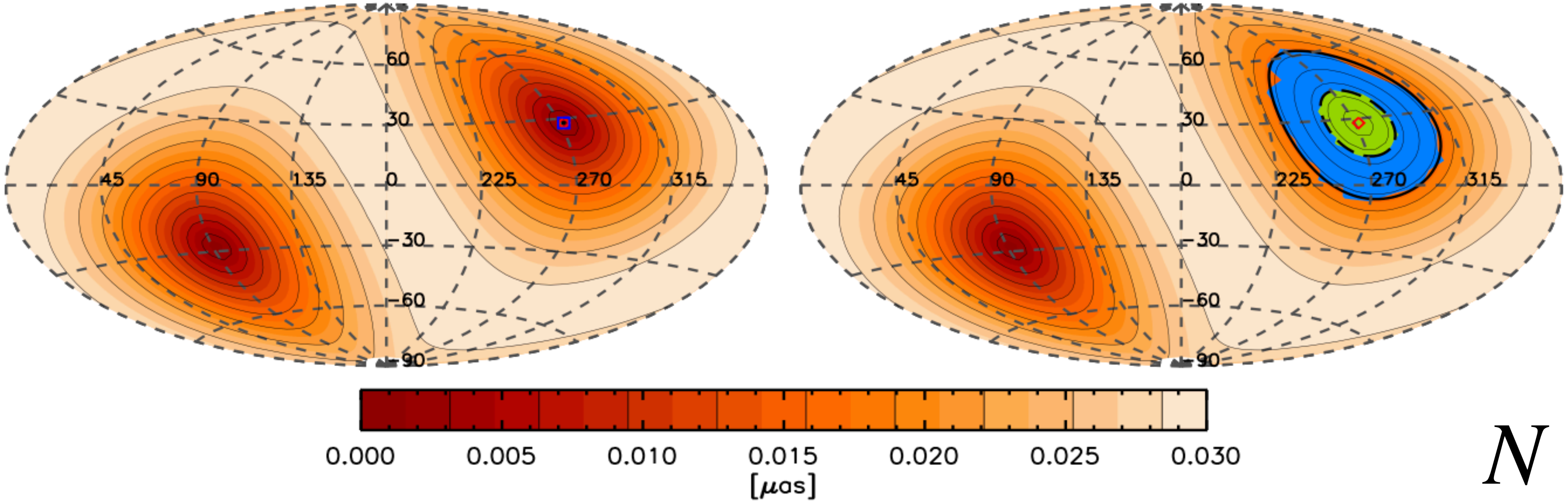
$\delta\beta < 30c^{-1}km/s$ (68%)

Observational signatures of the Cosmic Aberration Drift



Observational signatures of the Cosmic Aberration Drift

Reconstruction of the signal via spherical harmonics decomposition of the AD vector field $\Theta = \nabla \cdot d\vec{\theta}\,' = \sum_{l,m} \Theta_{lm} Y_{lm}$



$N = 10^6$

EoM $\sigma = 0.6\ \mu as\ \mathrm{yr}^{-1}$

EoM $\sigma = 1.4\ \mu as\ \mathrm{yr}^{-1}$

Characteristic features:

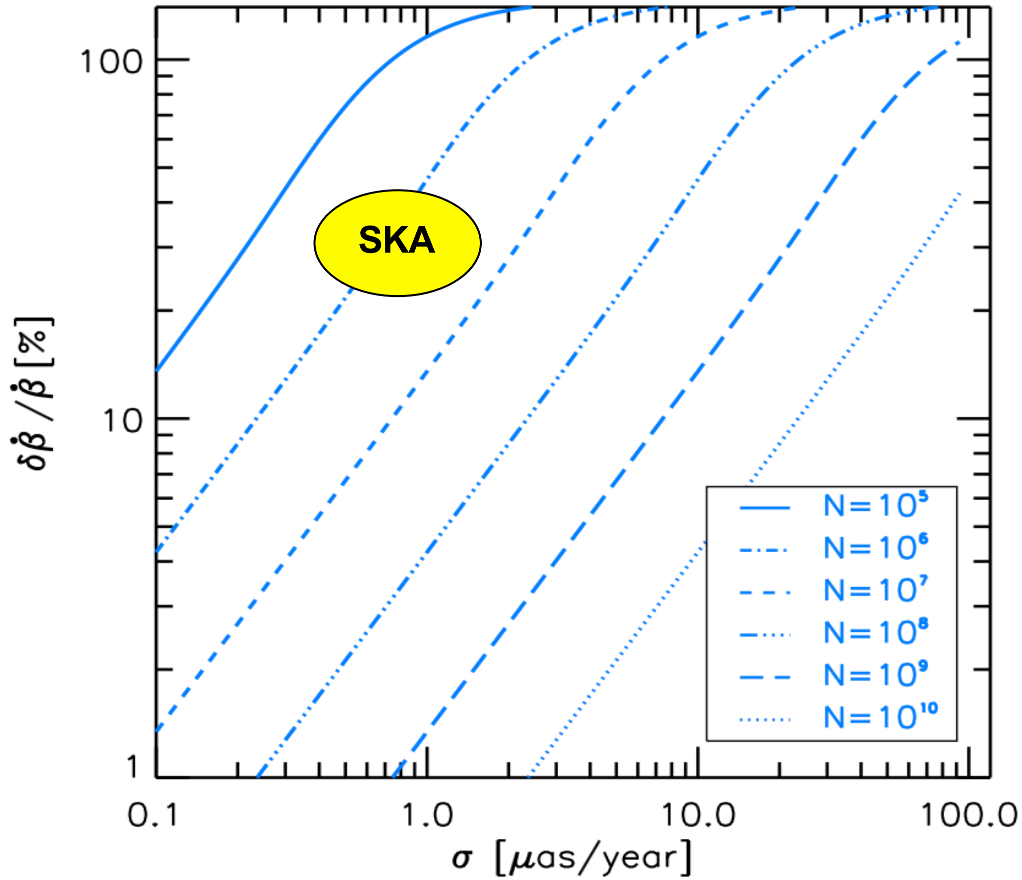
- Sinusoidal amplitude,

- Distance-independent

-The acceleration dipole (CAD is aligned with the velocity dipole of the CMB!

$$\nabla\Phi \propto \vec{\beta}$$

Precision on the amplitude and direction of the acceleration dipole



$$\sigma_\Omega = -\frac{3\pi}{N}\left(\frac{\sigma}{\dot\beta}\right)^2 \ln(1-p)$$

$$\frac{d\dot\beta}{\dot\beta} = \sqrt{\frac{3}{2N}}\,\frac{\sigma}{H_0\beta\left(1-\frac{3\Omega_m}{2}\frac{\mu}{f}\right)}$$

SKA

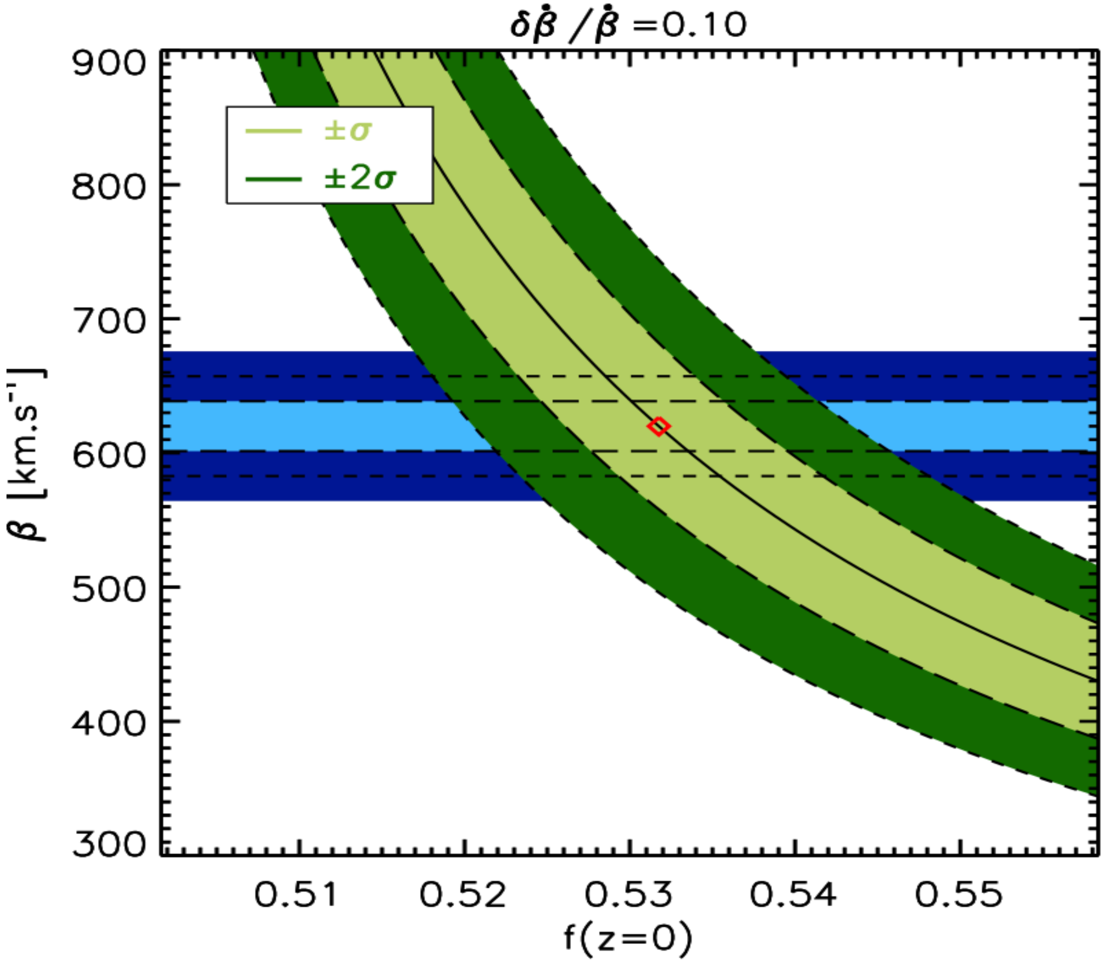
30% precision on CAD amplitude (68% c.l.)

5% precision on CAD direction (68%c.l.)

Beyond GAIA missions

GaiaNir (Hobbs et al 2017)

Precision on the amplitude and direction of the acceleration dipole



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Beyond GAIA missions

GaiaNir (Hobbs et al 2017)

CMB-independent evidences on amplitude and direction of velocity dipole

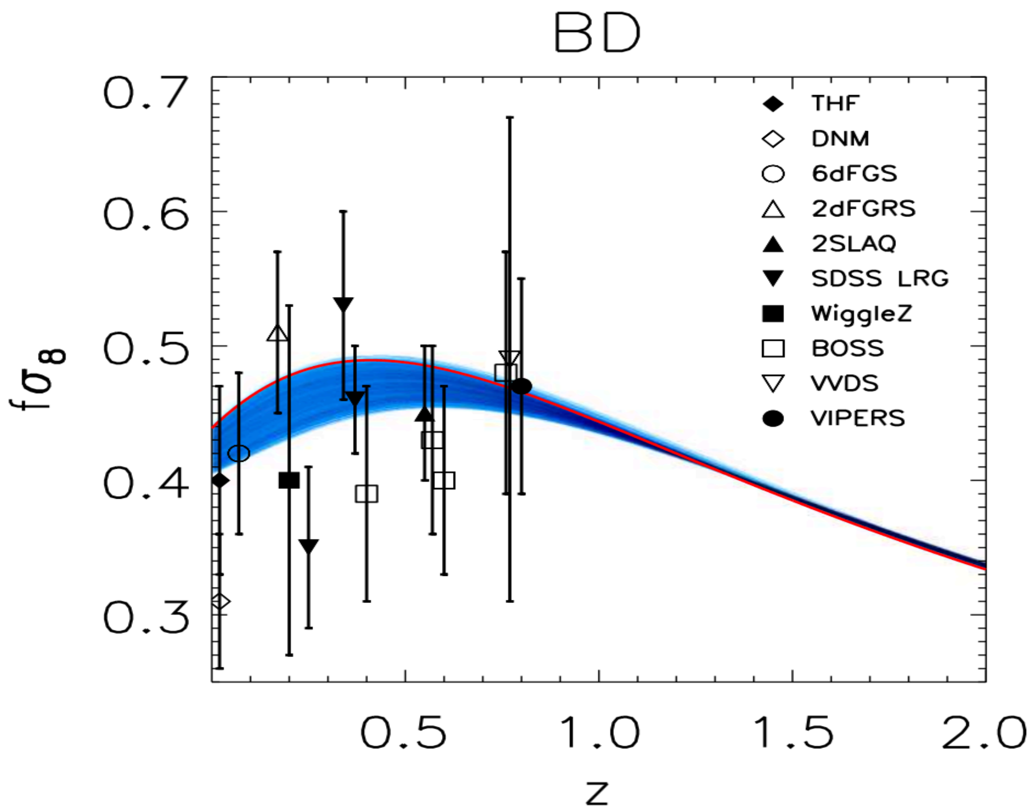
(See Aghanim et al . 2013 for CMB dependent test)

Predicting the expected signal in modified gravity scenarios

We considered the Hordenski class of MG models (in the EFT language)

Linear Perturbations theory in the quasi-static limit fully capured by incorporanting an effective gravitational constant into the Poisson field equation

$$\Delta\Phi = 4\pi G_N \bar{\rho}_m \delta_m a^2 \mu$$



Piazza Steigerwald & Marinoni 2014
Perenon, Piazza, Marinoni & Hui 2015
Perenon, Marinoni & Piazza 2017

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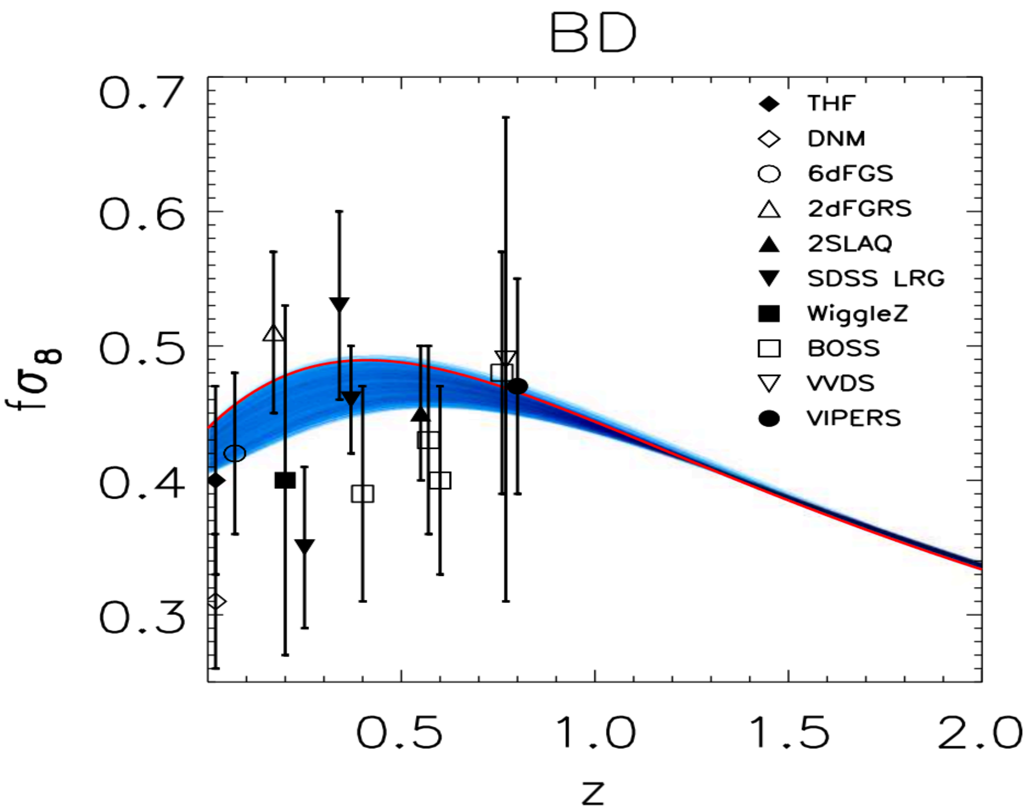

Piazza Steigerwald & Marinoni 2014
Perenon, Piazza, Marinoni & Hui 2015
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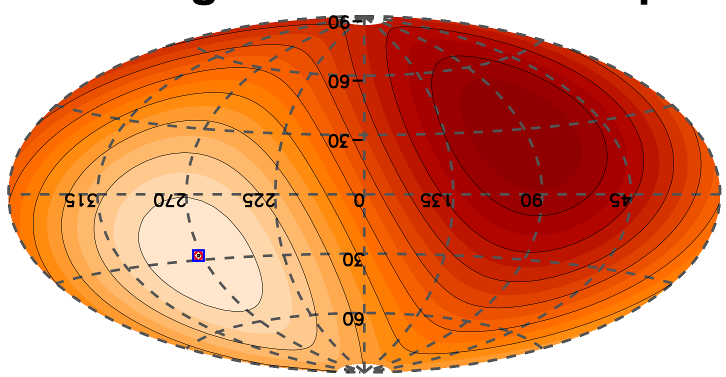
Gaia could already rule out local gravity with μ/f>18

$$\dot{\vec{\beta}} = -H\vec{\beta}\left(1 - \frac{3\Omega_m \mu}{2f}\right)$$

Distinctive Feature:

Acceleration dipole anti-aligned w/r to CMB dipole



Conclusions

Astrometry may provide insights on fundamental physics and gravitation.
Historically high precision astrometry was instrumental for testing GR.

Proposal to detect acceleration of the LG-centric observer w/r to distant sources.
What local dynamics tell us about the global universe?

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The **Cosmic Aberratoin Drift** signal is:
weak : need EoM proper motion accuracy 1μas/yr for 10^6 sources.
characteristic: acceleration dipole aligned with CMB velocity dipole,
redshift-independent.

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Real time cosmology not yet real cosmology!
….. Unless the `real' model is not the standard LCDM!

SKA may provide first detection.
Science case for sub-μas beyond GAIA missions