Real-Time Cosmology with Cosmic Parallax & Redshift Drift

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Dark Energy: the 3-fold way out

- Usual 2 ways of explaining dark energy:
  
  \[ G_{\mu\nu} = 8\pi G T_{\mu\nu} \]

  *Modified Gravity*

  - f(R), f(G), Unimodular, DGP, Horava-Lifshitz, extra dimensions, Einstein-Aether, degravitation, Cardassian, branes, strings...

  - *New fundamental fields*

  - Quintessence, Quartessence, K-essence, Chaplygin gas, interacting fields, vector fields, n-Forms, Braiding fields...

- Actually, there is a **third** way out!

  - Keep Einstein theory and “normal” (cold + baryonic) matter
  - Change the **metric**
Homogeneity and Isotropy

The most basic (and old) tenets of cosmology

Friedmann-Lemaître Robertson Walker (FLRW) metric:

- most general homogeneous and isotropic metric
- overwhelmingly successful at describing the universe in large-scales
- *Consistent* with all current observations

$$ds^2 = -dt^2 + \frac{a^2(t)}{1 + kr^2} dr^2 + a^2(t) d\Omega^2$$

Hard to probe directly → *lightcone* vs. *const. time* slices:

- Possibility → more exotic models may also be *consistent* with data
  - e.g.: void models
Why study void models?

- Huge (Gpc) voids can mimic the Hubble diagram without the need for dark energy!
  - Acceleration → artifact of wrong assumption on homogeneity
- Correct placement of 1st peak of CMB*
- 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!
Lemaître-Tolman-Bondi models

- LTB metrics describe void models

\[ ds^2 = -dt^2 + \frac{[\partial R(t, r)/\partial r]^2}{1 + \beta(r)} \, dr^2 + R^2(t, r) \, d\Omega^2 \]
Constraints on Void Models

- Voids which are too large (> 3 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)*

- Constraints on void shape from SDSS LRG or SNe number counts?
The Redshift Drift

- Even in $\Lambda$CDM, the redshift $z$ of a source is not constant.

- The evolution of $z$ was first estimated by Sandage in 1962!
  \[ \Delta_t z_s = H_0 \Delta t_0 \left( 1 + z_s - \frac{H(z_s)}{H_0} \right) \]

- This effect is called Redshift-Drift (or Sandage effect).
  - Model dependent!

- Very accurate spectroscopy can be used to distinguish between such models.

*Balbi & Quercellini, 0704.2350 (MNRAS)*

*Uzan, Clark & Ellis, 0801.0068 (PRL)*
E-ELT and CODEX in 1 slide

- **European Extremely Large telescope (E-ELT):**
  - Estimated completion: 2017
  - Aperture (diameter): 42m
  - Type: optical to mid-infrared
  - Cost: 960M € (including 1st generation instruments)


- **Cosmic Dynamics Experiment (CODEX):**
  - High resolution super-stable spectrograph in E-ELT
  - Precursor in VLT (2014): ESPRESSO (Echelle SPectrograph for Rocky Exoplanet- and Stable Spectroscopic Observations)

  *J. Liske et al., 0802.1532 (MNRAS)*
Redshift Drift in Dark Energy models

Balbi & Quercellini, 0704.2350 (MNRAS)
Redshift Drift in LTB

- The Sandage Effect (or redshift drift) in LTB is **very different** from $\Lambda$CDM!

<table>
<thead>
<tr>
<th></th>
<th>5 years</th>
<th>10 years</th>
<th>15 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Models I / II</td>
<td>1.1$\sigma$</td>
<td>6.2$\sigma$</td>
<td>12.5$\sigma$</td>
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<tr>
<td>cGBH Model</td>
<td>0.5$\sigma$</td>
<td>4.3$\sigma$</td>
<td>9.2$\sigma$</td>
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</table>

*Quartin & Amendola 0909.4954 (PRD)*
Gaia in 1 slide

- **Gaia** for cosmologists:
  - astrometry measurements with an accuracy of about 10 – 200 μas
  - astrometric measurements of some 500,000+ distant quasars

- Cost: ~700M €

- Broad scientific goals

- Allows us to detect large-scale deviations from isotropy through observations of proper motions of quasars

*Quercellini, Quartin & Amendola  0809.3675 (PRL)*

*Quercellini, Cabella, Amendola, Quartin & Balbi  0905.4853 (PRD)*
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.
Cosmic Parallax with Gaia (2)

- Off-center distance → 30 Mpc.

<table>
<thead>
<tr>
<th>Model</th>
<th>20 years</th>
<th>30 years</th>
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</thead>
<tbody>
<tr>
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<td>4.9σ</td>
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<tr>
<td>Model II</td>
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<td>2.2σ</td>
</tr>
<tr>
<td>cGBH Model</td>
<td>.6σ</td>
<td>2.6σ</td>
</tr>
</tbody>
</table>

Quartin & Amendola 0909.4954 (PRD)
Cosmic Parallax with Gaia (3)

- SNe → off-center dist. $d_{\text{obs}} \leq 15\%$ of void radius (~250 Mpc)
- CMB dipole → off-c. dist. $d_{\text{obs}} \leq 2\%$ of void radius (~30 Mpc)

**Off-center distance constrains (Mpc)**

<table>
<thead>
<tr>
<th>Model</th>
<th>6 years</th>
<th>10 years</th>
<th>20 years</th>
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</thead>
<tbody>
<tr>
<td>Model I</td>
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<td>66</td>
<td>23</td>
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<tr>
<td>Model II</td>
<td>235</td>
<td>109</td>
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<tr>
<td>cGBH Model</td>
<td>214</td>
<td>99</td>
<td>35</td>
</tr>
</tbody>
</table>
Real-Time Cosmology

- Cosmic parallax and the Sandage Effect are but two of the recently proposed Real-Time Cosmology observable effects.

- radial
  - redshift drift
- transverse
  - cosmic parallax
- global (velocity)
- local (acceleration)
  - proper acceleration
  - peculiar acceleration

Amendola, Balbi, Quartin & Quercellini (in prep)
Conclusions

- Redshift-drift → competitive consistency test of FLRW metric;
  - $5\sigma$ with 10 years of operation

- Cosmic Parallax vs. other anisotropy probes
  - CMB dipole is completely degenerated with our peculiar velocity
  - Other CMB multipoles: assume anisotropy is not growing

- Complementary with supernovae:
  - Need ~ 700 SNe for same sensitivity of Gaia

- Gaia's sky map can be compared with the next global-astrometry mission
Conclusions (2)

- 2 light cones are better than 1
- Redshift drift – inhomogeneity probe
- Cosmic parallax – anisotropy probe
- Both signals effectively increase as $\Delta t^{3/2}$
- The near future → dawn of Real Time Cosmology

Thanks!
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)

Amendola, Balbi, Quartin & Quercellini (in prep)
Noise and Sistematics

Most **obvious** source of noise → peculiar velocities

\[ \Delta t \gamma_{\text{pec}} = \left( \frac{v_{\text{pec}}}{500 \text{ km/s}} \right) \left( \frac{D_A}{1 \text{ Gpc}} \right)^{-1} \left( \frac{\Delta t}{10 \text{ years}} \right) \mu \text{as} \]

- Overall effect → ~ 0.1 μas / year
- On the very large scales involved they are uncorrelated!

**Competing dipolar signatures:**

- changing aberration due to acceleration of the solar system
  
  *Kovalevsky 2003*  (*Reid et al. 2009*)

- dipolar signal due to motion of observer
Noise and Sistematics (2)

- \( \Delta_t \gamma \) for 2 quasars separated by 90°, at different redshifts

Quartin & Amendola 0909.4954 (PRD)
Estimating the Cosmic Parallax

- Calculating the Cosmic Parallax require solving the full LTB geodesic equations.
- Simple, inconsistent estimate $\rightarrow$ flat FRW universe with $H(t) \rightarrow H(t, r)$.
- Assume 2 sources initially at $(X_a, \theta_a)$ and $(X_b, \theta_b)$.

\[ \Delta t \gamma = \Delta t (H_{\text{obs}} - H_X) X_{\text{obs}} \left[ \frac{\sin \theta_a}{X_a} - \frac{\sin \theta_b}{X_b} \right] \]
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 stars → 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 CODEX

- Estimated CODEX precision:

\[
\sigma_{\Delta v} = 1.35 \left( \frac{S/N}{2370} \right)^{-1} \left( \frac{N_{\text{QSO}}}{30} \right)^{-\frac{1}{2}} \left( \frac{1 + z_{\text{QSO}}}{5} \right)^{-1.7} \text{ cm/s}
\]

\[
\Delta v = c \Delta t z_s / (1 + z)
\]

- Signal-to-noise ratio per pixel:

\[
\frac{S}{N} = 700 \left[ 10^{0.4(16 - m_X)} \right] \left( \frac{D}{42 \text{ m}} \right)^2 \left( \frac{t_{\text{int}}}{10 \text{ h}} \right) \left( \epsilon \right) \left( 0.25 \right)^{\frac{1}{2}}
\]

apparent magnitude
LTB models (3)

- Hubble parameter is no longer unique

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

\[
H_{\parallel} = \frac{1}{R'} \frac{\partial F}{\partial t}
\]

\[
H_{\perp} = \frac{1}{R} \frac{\partial l}{\partial t}
\]
Cosmic Parallax FoM

- Figure of Merit (FoM) for Cosmic Parallax:
  - Useful quantity to compare future astrometric missions (for cosmic parallax):
    \[ \sqrt{N_{QSO}} \left( \frac{\Delta t}{1 \text{ year}} \right) \left( \frac{\sigma_p}{1 \mu\text{as}} \right)^{-1} \]

- Gaia \( \rightarrow \) FoM = 39
- SIMLite \( \rightarrow \) FoM = 9
- 2 Gaia Missions 15 years apart \( \rightarrow \) FoM = 230!!!
Cosmic Parallax with Gaia

- SNe → off-center dist. $X_{\text{obs}} \leq 15\%$ of void radius (~250 Mpc)
- CMB dipole → off-c. dist. $X_{\text{obs}} \leq 2\%$ of void radius (~30 Mpc)

**Caveat:** this assumes zero velocity between observer and the center of the void

- With a typical velocity of 500 km/s: $X_{\text{obs}} \leq 60$ Mpc.

Blomqvist & Mortsell: 0909.4723
The Extremely Large Telescope is the essential next step in mankind’s direct observation of the nature of the universe. It will provide the deeper insights into the universe that will underlie our developing understanding of its nature.
Cosmic Parallax in other models

- The cosmic parallax effect is sensitive to any kind of anisotropy;
- Measurement of late-time anisotropy!
  - Present anisotropy $\rightarrow$ anisotropic pressure field!
- Overall effect can be higher in, e.g., Bianchi I
- Different anisotropic models $\rightarrow$ different multipole dependence;

Koivisto & Mota
arXiv:0801.3676 (JCAP)