Cosmologia em Tempo-Real
com
Efeito Sandage
e
Paralaxe Cósmica

Miguel Quartin
Instituto de Física
Univ. Federal do Rio de Janeiro
Dark Energy in 2 slides

- Observational evidence for dark energy:
  - Cosmic Background Radiation (CMB) → Nobel Prize 2006
  - Supernovae → Nobel Prize 2011
  - Matter power spectrum in large scale structure
  - Age of the Universe > age of oldest stars
  - Baryon Acoustic Oscillations

- A universe with only standard model particles + dark matter cannot explain any of the above!
Dark Energy in 2 slides

\[ \Omega_m + \Omega_\Lambda = 1 - \Omega_k \]

- N.B.: BAO \rightarrow Baryon Acoustic Oscillations ↔ matter power spectrum

Type Ia Supernovae
Type Ia Supernovae (2)

- Standardizable candles

**Measuring Distances with Standard Candles**

An Object becomes fainter by the square of its distance

- 100
- 0.5 metre
- 1 metre

- 25
- 0.5 metre

An Object becomes fainter by the square of its distance
Cosmic Microwave Background Radiation (CMB)

- Oldest photons in the Universe: redshift $z \sim 1100$
- Nearly-isotropic 2.725 K radiation
  - Anisotropies: $\sim 1$ part in $10^5$
  - Temperature of CMB $\leftrightarrow 13.6$ eV (ionization of H)
CMB (2)

- Angular power spectrum (↔ spher. harmon. decompos.)
Matter Power Spectrum (linear)

- Initial conditions (CMB)
  + linear perturbation theory

Tegmark et al. 2002

Legend:
- Cosmic Microwave Background
- SDSS galaxies
- Cluster abundance
- Weak lensing
- Lyman Alpha Forest

Wavenumber $k$ [$h/\text{Mpc}$]

Current power spectrum $P(k)$ [$\text{[h}^{-1}\text{Mpc}]^3$]

Wavelength $\lambda$ [$h^{-1}\text{Mpc}$]
Matter Power Spectrum (non-linear)

$z = 14.5$

50 Mpc/h
Baryon Acoustic Oscillations
Baryon Acoustic Oscillations (2)

Dark Matter, Gas, Photon, Neutrino

110 yrs

z=82507

Mass Profile of Perturbation

Radius (Mpc)
Baryon Acoustic Oscillations (3)
**Dark Energy: the 3-fold way out**

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

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

- **New fundamental fields**
  - Quintessence, Quartessence, K-essence, Chaplygin gas, interacting fields, n-Forms, vector fields, 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

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

- Hard to probe directly → lightcone vs. const. time slices:
  - Possibility → more exotic models may also be consistent with data
    - e.g.: void models; anisotropic models; ...
Homogeneity?

- LTB metric (spher. symmetric, inhomogeneous) → Gpc
  - Void models

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

- Surprisingly successful as an accelerating model without Dark Energy;
- Can fit all observations in the light cone SNe, BAO & CMB
- But may fail for observations inside the light cone (kSZ, redshift drift & CMB blackbody spectrum)

Marra, Notari 1102.1015 (CQG)  
Zhang, Stebbins 1009.3967 (PRL)

Quartin, Amendola 0909.4954 (PRD)  
Caldwell, Stebbins 0711.3459 (PRL)
Isotropy?

People usually consider 2 possible anisotropies

- Shear
- Vorticity

But there is a 3\textsuperscript{rd} type of anisotropy: (spatial) curvature anisotropy

- Basically: the 3-curvature can be different in different directions
- There exists aniso. curv. models which are
  - Homogenous
  - Irrotational
  - Shear-free

Are we taking supposed symmetries too seriously?

\textbf{Koivisto, Mota, Quartin, Zlosnik 1006.3321 (PRD)}
Precision Cosmology vs. Accurate Cosmology

1%
Void Models

- Huge (Gpc) voids can mimic the Hubble diagram without the need for dark energy!
  - Acceleration → artifact of wrong assumption on homogeneity
- Not over complicated
- Could arise from
  - back-reaction effects → one of many bubbles
  - eternal inflation scenarios
  - … ?
- Isotrope, if observer is in the center
  - No a priori reason for that → unlikely!
Lemaître-Tolman-Bondi models

- LTB metrics describe void models

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

- Exact solution in a matter-dominated era

\[ R(t, r) = (\cosh \eta - 1) \frac{\alpha(r)}{2k(r)} \]

\[ t = (\sinh \eta - \eta) \frac{\alpha(r)}{2k(r)^{3/2}} \]
LTB models \((2)\)

- Void matter density profile
LTB models (3)

- Hubble parameter is no longer unique

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

\[ H_{\parallel} = \frac{1}{R'} \frac{\partial R'}{\partial t}; \quad H_{\perp} = \frac{1}{R} \frac{\partial R}{\partial t} \]

- Baryon Acoustic Oscillation signal depends on \( H_{\parallel} \)

- SNe observations are only related to \( H_{\perp} \)

García-Bellido & Haugbolle: 0802.1523 (JCAP)
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)
  - $kSZ$ at small scales due to free $e^-$
    - Zhang & Stebbins 1009.3967
- Recent work:
  - Biswas, Notari & Valkenburg: 1007.3065
  - Marra & Notari: 1102.1015
The Redshift Drift

- Even in ΛCDM, 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)*
The Extremely Large Telescope is the essential next step in mankind’s direct observation of the nature of the universe. It will prove the design works as planned and will underlie our developing understanding of its nature.
E-ELT and CODEX in 1 slide

- **European Extremely Large telescope (E-ELT):**
  - Estimated completion: 2020-22
  - Aperture (diameter): 39-42m
  - Type: optical to mid-infrared
  - Cost: ~1 B€ (including 1st generation instruments)
  - Brazil is joining ESO!


- **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>Model</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>
</tr>
<tr>
<td>cGBH Model</td>
<td>.5$\sigma$</td>
<td>4.3$\sigma$</td>
<td>9.2$\sigma$</td>
</tr>
</tbody>
</table>

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

- **Gaia** for cosmologists:
  - astrometry measurements with an accuracy of about $10 - 200 \mu\text{as}$
  - 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)**
In a FRW metric, $\Delta_t \gamma = \gamma_2 - \gamma_1 = 0$.

In any anisotropic metric, however, $\Delta_t \gamma \neq 0$, and we have cosmic parallax.
 Cosmic Parallax with Gaia

- Off-center distance $\rightarrow$ 30 Mpc.

<table>
<thead>
<tr>
<th>Model</th>
<th>20 years</th>
<th>30 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model I</td>
<td>1.8(\sigma)</td>
<td>4.9(\sigma)</td>
</tr>
<tr>
<td>Model II</td>
<td>.5(\sigma)</td>
<td>2.2(\sigma)</td>
</tr>
<tr>
<td>cGBH Model</td>
<td>.6(\sigma)</td>
<td>2.6(\sigma)</td>
</tr>
</tbody>
</table>

Quartin & Amendola 0909.4954 (PRD)
Cosmic Parallax with Gaia (2)

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

Off-center distance constrains (Mpc)

<table>
<thead>
<tr>
<th>Model</th>
<th>6 years</th>
<th>10 years</th>
<th>20 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model I</td>
<td>143</td>
<td>66</td>
<td>23</td>
</tr>
<tr>
<td>Model II</td>
<td>235</td>
<td>109</td>
<td>39</td>
</tr>
<tr>
<td>cGBH Model</td>
<td>214</td>
<td>99</td>
<td>35</td>
</tr>
</tbody>
</table>
Cosmic Parallax in other models

- The cosmic parallax effect is sensitive to “any kind” of anisotropy (technically, to the shear);
- Measurement of late-time anisotropy!
- Primordial anisotropy gets diluted with expansion
  - 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)
The “Bianchi I” Metric

- Bianchi I metric

\[ ds^2 = -dt^2 + a^2(t)dx^2 + b^2(t)dy^2 + c^2(t)dz^2 \]

- Flat, no overall vorticity

- Non-zero shear

\[ \Sigma_x \equiv \frac{H_x}{H} - 1 \neq 0 \]

\[ H \equiv \frac{1}{abc} \frac{d}{dt} (abc) \]
Cosmic Parallax in Bianchi I

\[ \theta_B = \phi_B = 0 \quad \text{and} \quad \theta_B = \pi/2, \phi_B = 0 \]

\[ \sim 0.2 \, \mu\text{as} / \text{year} \]

Quercellini, Cabella, Amendola, Quartin & Balbi 0905.4853 (PRD)
Anisotropies in Cosmology (2)

- People usually consider **2 possibilities**
  - Shear
  - Vorticity
- But there is a 3\textsuperscript{rd} type of anisotropy: (spatial) \textit{curvature anisotropy}
  - 3-curvature can be different in different directions
  - There exists aniso. curv. models which are
    - Homogenous
    - Irrotational
    - Shear-free
      - NO Cosmic Parallax!
CP and the CMB Dipole

- CMB Dipole → assumed to be ~99% due to our own peculiar velocity;

- No bulk motion between Quasars and CMB

- Reasonable, but how do we test this?
  - Look at other diffuse backgrounds!
  - E.g.: cosmic rays, X-rays, gamma-rays, FIR
    - Very hard to isolate the background!
  - Look at off-diagonal CMB correlations!

Amendola, Catena, Masina, Notari, Quartin & Quercellini 1008.1183
CP and the CMB Dipole (2)

- Gaia in 6 years with 1,000,000 QSOs (preliminary):
  - Measure pec. veloc. with $\Delta v = \pm 150 - 250$ km/s
  - $2 - 3\sigma$ distinction between “tilted universe” & standard model

Quartin & Atrio-Barandela (in prep)
Real-Time Cosmology

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

Quercellini, Amendola, Balbi, Cabella & Quartin (1011.2646)
### Real-Time Cosmology (2)

<table>
<thead>
<tr>
<th></th>
<th>radial</th>
<th>transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>global (velocity)</td>
<td>redshift drift</td>
<td>cosmic parallax</td>
</tr>
<tr>
<td>local (acceleration)</td>
<td>peculiar acceleration</td>
<td>proper acceleration</td>
</tr>
</tbody>
</table>

- Pecul. accel. $\rightarrow$ measure accel. of stars inside Milky Way $\rightarrow$ e.g. distinguish between Newton or MoND
  
  *Amendola, Quercellini & Balbi* 0708.1132 (Phys.Lett.B)

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

  *Quercellini, Amendola, Balbi, Cabella & Quartin* (1011.2646)
Conclusions

- LTB is less symmetric than FLRW
  - FLRW less symmetric than static universe
- Redshift-drift → competitive consistency test of FLRW metric;
  - $5\sigma$ with 10 years of operation
- “Cosmic parallax” is not a regular parallax!
  - Anisotropy test → measures present anisotropy
  - It may be observable by Gaia, but not in void models
Conclusions (2)

- Cosmic Parallax *vs.* other anisotropy probes
  - CMB dipole is 100% 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

- One of the *few* probes of our peculiar velocity
  - and the *intrinsic* CMB dipole!
Conclusions (3)

- 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
“Tudo que se vê não é
Igual ao que a gente
Viu há um segundo
Tudo muda o tempo todo
No mundo

Não adianta fugir
Nem mentir pra si mesmo agora
Há tanta vida tantos fótons lá fora

Aquí dentro sempre

Como uma onda no mar
Como uma onda no mar”

Lulu Santos
More on Gaia

- Astrometric precision depends strongly on magnitude
- Quasar distrib. peaks at $z \approx 1.4$ (mag $G = 19 - 20$)
More on CODEX

- Estimated CODEX precision:

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

\[ \Delta v = c \Delta t \frac{z_s}{(1 + z_s)} \]

- Signal-to-noise ratio per pixel:

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

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

- Baryon Acoustic Oscillation signal depends 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)_
Noise and Sistematics

- Most **obvious** source of noise $\to$ peculiar velocities

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

- Overall effect $\to$ $\sim 0.1 \mu\text{as} / \text{year}$
- 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)

- $\Delta \gamma$ for 2 quasars separated by $90^\circ$, at different redshifts
Cosmic Parallax with Gaia

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

  Alnes & Armazguioui: astro-ph/0607334 (PRD)
  astro-ph/0610331 (PRD)
  Blomqvist & Mortsell: 0909.4723 (JCAP)

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

- With a typical velocity of 500 km/s: $d_{\text{obs}} \leq 60$ Mpc.
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
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 → FoM = 39
- SIMLite → FoM = 9
- 2 Gaia Missions 15 years apart → FoM = 230!!!