Dipole Cosmology:
The Copernican Paradigm Beyond FLRW

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Executive Summary:

- My talk today is about a certain kind of anisotropic Bianchi cosmology that generalizes the FLRW framework, which we call "Dipole Cosmology".
- These cosmologies, we will argue, are the simplest generalization of FLRW that can incorporate a flow in the cosmic fluid stress tensor.

- If you are like me, you probably always thought of Bianchi models as only of formal interest.
- In a Universe which is accelerating, there are fairly generic statements called Cosmic No Hair Theorems [eg. Wald], that say that shear anisotropies should always die down at late times.
- But there have also been various tentative claims about observations of dipole/flow anisotropies in quasars, galaxies, etc. (Some references later.)

What lead me to the current work is two questions –

- What is the simplest (most symmetric) generalization of the FLRW set up that can allow a flow?

  We find that the answer is a class of tilted type V/VII$_h$ Bianchi spacetimes which are homogeneous on spatial slices, but with only U(1) isotropy around every point. This is what we call "Dipole Cosmology".

- Do these flows have to die down at late times?

  No! In very broad classes of cases, the flow can increase slowly at late times, even though the shear dies down in accordance with CNH theorems. In other words, FLRW framework has a weak (but fairly generic) instability towards the growth of dipoles at late times, despite CNH.

So theoretically, late time cosmic dipoles are not ruled out.

Along the way, we will also show that dipole cosmology has a set of generalized Friedman equations which are quite simple, and serves as a model building paradigm with mixtures of fluids, just as the FLRW setting is. I will show you these equations.

So it may be worth exploring.

Take II:

- The idea that we are non-privileged oservers has been a remarkably successful idea in the history of science.
- Ever since Copernicus, we have occupied an increasingly non-central place in our cosmological worldview. (Latest eg: multiverse).
- Even though Copernicus probably did not quite say it in so many words, the key idea here seems to be that we are (in some suitable sense) generic observers.
- We will call this the Copernican paradigm or Copernican principle.

- In this talk, I will emphasize that the notion of what exactly we mean by a Copernican cosmology, depends on our priors.
- In other words, “generic” should be understood as generic among a class of observers that are defined by our priors.

- We will use this philosophy to identify a minimal cosmological ansatz and equations of motion that allows the possibility of a cosmic flow in the Universe.
- We will view this as a model-building paradigm that is analogous to the FLRW ansatz and Friedmann equations in a Universe without a flow.

- Motivation? Many papers by many authors spanning many years including some of ours (with Mohayaee, O'Colgain, Sheikh-Jabbari and Yin) that hint that the CMB dipole may not be entirely kinematic.
- A recent 4.9 σ observation [Secrest et al.] regarding quasar angular distributions at $z \sim 1$, is the one that made me consider this (somewhat) seriously as a theoretical possibility. See also earlier works by [Singhal, Mikgas et al, ...]. (Many others...)
- Even though the dipole is tentative, we therefore ask the question: what happens if we take the possibility that the CMB dipole is not entirely kinematic, and is the result of a cosmic flow, seriously?
- Aside on intrinsic vs non-kinematic dipole.

Broader motivations:

- Late time Universe is ripe with observational tensions (H_0, S_8) ...
- ... and theoretical challenges (no satisfactory UV complete construction of an accelerating Universe).
- These beg the question: what are the places where our current paradigm may have cracks?
- I want to be maximally conervative and not modify gravity, etc.

- Lets start with the question: What is the most Copernican Universe? (if there are no assumptions made other than number of dimensions and signature)
- This idea is often encapuslated in the so-called Perfect Cosmological Principle.
- It states that we are non-privileged observers in both space and time.
- One way to realize this would be if our universe was a maximally symmetric spacetime, eg. Minkowski space.

- But observations over the last century give us quite some confidence that the Universe is time-dependent, had a Big Bang, etc.
- This lead us to revise the prior and only then look for the most symmetric ansatz.
- This philosophy is what I will mean by the Copernican paradigm in cosmology: We look for the most symmetric spacetime that is compatible with our basic prejudices/priors.

- Expansion/time-dependence suggested that we look for a spatially symmetric Universe.
- The minimal (ie., most Copernican) guess here would be that the spatial slice is maximally symmetric. This is the Cosmological Principle.
- Maximal symmetry on a spatial slice means technically that there is a group of symmetries of dimension 6 acting transitively on the spatial slice.
- This fixes the metric uniquely to be in the FLRW class.

- But in today's talk, we want to investigate the possibility that the universe may have a flow which is responsible (at least partially) for the CMB dipole.
- We will need to revise our Copernican anatz from FLRW to one that incoporates a flow.
- How should we revise our priors?

- What is the most symmetric ansatz that is compatible with a cosmic flow ("tilt") in some spatial direction, along with expansion in the time direction?
- We can call it the Special Cosmological Principle or Dipole Cosmological Principle.

- It turns out that the most symmetric generalization of FLRW compatible with such a flow is one where there is an axial isotropy, and the spatial slices are homogenous.
- Slightly more technically – our fluid spacetime has a preferred spatial direction around which it has an axial isotropy, it is of the Type V Bianchi class, and the fluid flow is not orthogonal to the surfaces of homogenity (ie., there is non-vanishing "tilt").
- It turns out that when there is an axial isotropy, type V and type VII_h Bianchi classes become identical [King-Ellis].

- With these choices the metric can be written as:

$$ds^2 = -dt^2 + a^2(t)\left[e^{4b(t)}dz^2 + e^{-2b(t)-2A_0 z}\left(dx^2 + dy^2\right)\right] \tag{1}$$

A_0 is a constant.

- The stress tensor is controlled by only one extra function β, which we will call the flow (tilt), and therefore the equations of motion are quite tractable.

$$T^{\mu}{}_{\nu} = T_{\text{iso}}{}^{\mu}{}_{\nu} + T_{\text{tilt}}{}^{\mu}{}_{\nu}, \qquad T_{\text{iso}}{}^{\mu}{}_{\nu} = \text{diag}(-\rho, p, p, p)$$

$$T_{\text{tilt}}{}^{\mu}{}_{\nu} = (\rho + p)\sinh\beta \begin{pmatrix} -\sinh\beta & ae^{2b}\cosh\beta & 0 & 0 \\ -\cosh\beta/(ae^{2b}) & \sinh\beta & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{2}$$

- In terms of

$$H := \frac{\dot{a}}{a}, \qquad \sigma := 3\dot{b} \tag{3}$$

the “Friedmann" equations become

$$H^2 - \frac{1}{9}\sigma^2 - \frac{A_0^2}{a^2}e^{-4b} = \frac{\rho}{3} + \frac{1}{3}(\rho + p)\sinh^2\beta \tag{4a}$$

$$\sigma = \frac{1}{4A_0}ae^{2b}(\rho + p)\sinh 2\beta, \tag{4b}$$

$$\dot{\rho} + 3H(\rho + p) = -(\rho + p)\tanh\beta(\dot{\beta} - \frac{2A_0}{a}e^{-2b}) \tag{4c}$$

$$\dot{p} + H(\rho + p) = -(\rho + p)\left(\frac{2}{3}\sigma + \dot{\beta}\coth\beta\right). \tag{4d}$$

- Note that we have two extra functions – one extra scale factor (or equivalently, shear) and also the fluid velocity β. To accommodate for these, we have precisely two extra equations.
- Note that the assumption of spatial homogeneity means that the Einstein equations are still ODEs just as in the FLRW case. They just contain two more fields.
- So the system is very tractable. We will suppress all details.

- When $\beta = 0$ one can consistently set A_0 to zero and set $b(t) = 0$ to get the flat FLRW equations.
- Note also that we can do model-building with mixtures, just as in FLRW.

- Some of these results can be obtained from some general results from the late 60's and early 70's by Ellis (with Stewart, with MacCallum, and with King).
- But this particular specialization of their results does not seem to have been explored. And it looks well-motivated if we take a Copernican/symmetry approach with large scale flows as a prior.
- Note also that we were able to write the EOMs in a very simple metric form (Ellis et al. typically work with vielbeins and spin connections to charetcterize symmetries and Einstein equations).
- The primary concern of the Ellis papers is with situations which have less symmetry than this, and therefore they generally deal with less Copernican spacetimes according to our criterion.

Late Time Phenomenology

- More pragmatically, only single fluids with constant equations of state were considered in these works.
- But when the total equation of state is time dependent, or when there are multiple fluids, the physics becomes interesting.
- In particular, quite generically in mixtures with radiation, the relative flow between matter and radiation can increase. This is sourced by a shear term that dies down at late times, and therefore may very well contribute to the CMB dipole.
- These results can be viewed as a (fairly) generic instability of the FLRW paradigm towards the growth of late time flows.

Punchlines, Take II:

- Anisotropies due to flows can get enhanced (quite generically) at late times, even when there is acceleration.
- Flow anisotropies are a loophole in Cosmic No-Hair Theorems.
- The Dipole Cosmology paradigm that we are lead to, has one extra scale factor, and a flow velocity corresponding to each matter component.
- Model building with mixtures is eminently possible. An immediate and simple generalization of the Friedmann equations. If there is only one fluid component, we get two extra equations on top of the usual two of Friedmann.
- ODEs $\implies$ easy to do evolution.

What Next?

- Does Dipole Cosmology framework help with late time tensions? Cosmography in dipole cosmology. Work in progress.
- Zero-ing in on flat LCDM in FLRW required not just observations of the background but also CMB anisotroies. In other words we need perturbation theory. This is more complicated, because we have broken the isotropy group from $SO(3)$ to $U(1)$.

- Thank You For Your Attention!