Dominik J. Schwarz (Bielefeld University) SKA Science Working Group Meeting November 2024

The largests cosmic scales and the source count dipole

Radio source count dipole and Gaussianity have been among SKA's 14 highlight science cases and there is even more reason than in 2014 to make the largest scales a prime traget for the SKA Fonseca et al. 2014, Schwarz et al. 2014 (AASKA14), Bacon et al. 2020 (Red Book)

Nature of cosmic dipoles

Cosmological principle

(statistical isotropy and homogeneity) implies the existence of cosmic time, preferred rest frame, and comoving observers

This cosmic rest frame must be universal, i.e. the same at different redshifts ($z = 0$, 1 or 1000) and the same for all probes (CMB, AGNs, clusters, SNe, ...)

Can we find this common cosmic redshift in different cosmological probes?

How to probe the nature of the CMB dipole?

Planck 2020 $\ell = 1 : v = (1.23356 \pm 0.00045) \times 10^{-3}c$ $356 + 0.00015$

 $\ell \gg 1$: $v = (0.996 \pm 0.219) \times 10^{-3}c$ where the observed direction *n* ˆ is given by *n* ˆ = \sim 70 \sim \sim

Planck 2014, Saha et al. 2020 improve via better full sky maps (foregrounds!) should be done by LiteBIRD, CMB-S4 lacks sky coverage maps (foregrounds!)

frame is given by the Lorentz transformation (see, e.g., \sim

Is the CMB dipole purely kinematic? locity of our Solar System barycentre relative to a frame, called the *CMB frame*, in which the temperature disc α *a*1*m*, However, in completely subtracting the dipole, this frame would

CMB itself shows that high- ℓ modes are consistent with kinematic origin of CMB dipole which an observer would expect to see a dipole α iat high- ℓ modes are consistent The very two frames of the between the settlement is, however, howeve If *T*⁰ and *n* ˆ ⁰ are the CMB temperature and direction as

^ˆ ⁰ ·) , (2)

\blacksquare **diameter by the second derivative** *d* \overline{a} **d** \overline{a} $\mathbf{r} = \mathbf{r} \cdot \mathbf{r} = \mathbf$ variance estimate is also broken down into its aberration-type part, $\mathsf{D}\mathsf{I}\mathsf{a}\mathsf{n}\mathsf{n}\mathsf{b}$ ext. Planck 2014

Kinematic source count dipole given cell (*b*) and denote it 'mask n'. We use the 68 percentile of the rms maps as the upper bound and reject all cells with higher local noise than the 68% limit. In case of the 68% limit. In case of the TGSS and WENSS SURVEY, the local results in the radio survey, the radio survey is directly given in the radio survey is

For extragalactic sources at $z_{\text{median}} > 1$: and for the WENSS ⁶⁸ *^b* = 4.12 mJy/beam. While there is nc sources at $z_{\rm max}$ $>$ 1: \sim source catalogue available, we adopt the mask definition \sim

Counts-in-cell from surveys covering large areas Ellis & Baldwin 1984 om surveys covering large areas 1998). For the NVSS, we re-scale the mask 'NVSS65' of Chen

Frances radio conveyor of the TGSS-ADRIC of the TGSS x in various radio surveys: Siewert et al. 2021

$$
\frac{dN}{d\Omega}(>S,\mathbf{e}) = \frac{dN}{d\Omega}(\geq S) (1 + \mathbf{d} \cdot \mathbf{e} + \ldots),
$$

$$
\mathbf{d} = [2 + x(1 - \alpha)]\mathbf{v}/c, \quad S \propto \nu^{\alpha}, \quad \frac{dN}{d\Omega} \propto S^{-x}
$$

Power-law ansatz for x is not quite correct, but can be easily corrected (Tiwari et al. 2015)

Local structure and the cosmic radio dipole

- Simulations for SKA-MID Baseline Design included: Cosmic structure (LCDM), simple bias model, proper motion of observer, survey geometry **Survey** Thres. *c*¹ *c*² *c*³ *c*⁴ *c*⁵ *z*max *N*gal*/*10⁶ **SKAL AND DEEP BAND DEEP BAND DEEP BAND 2 SURVEY 5 SURVEY 5 SURVEY 5 SURVEY 5 SURVEY SURVEY SURVEY SURVEY SURVEY**
- Not included: multi-component aspect, multi-tracer aspect, bias evolution, galactic foregrounds, calibration systematics, errors on photo-z's
	- CMB dipole
	- structure dipole \bullet
	- kinematic & structure dipole
	- kinematic & structure dipole, w/o local structure

8σ 4.939 1.027 14.125 0.913 −0.153 0.329 2.04

Figure 10. Dipole directions (left) and histogram of dipole amplitudes (right) based on 100 LSS simulations each for a flux density threshold of 22.8µJy at 700 MHz without kinetic dipole (pink), with kinetic dipole (purple) and with the contribution from the local structure dipole removed (red). The blue dot shows the direction of the CMB dipole. The results are displayed in galactic coordinates and in stereographic projection.

Bengaly et al. 2019; SKA Cosmology Science Working Group: Bacon et al. 2020

Radio and quasar dipoles

(Blake & Wall 2002, Singal 2011, Rubart & Schwarz 2013, Tiwari et al. 2015, Singal 2019, Siewert et al. 2021, Secrest et al. plake & Wail 2002, Olligal 2011, Hubart & Scriwarz 2013, Tiwari et al. 2013, Siligal 2019, Siewert et al. 2021, Secres
2021, 2022, Dam et al. 2022, Wagenveld et al. 2023, Mittal et al. 2024, ...) $\frac{1}{2}$

Radio and quasar dipoles show excess dipole

Fig. 7. Dipole amplitudes with 3 uncertainties compared to the amplitude from kinematic dipole and Siewert et al. (2021) and Secretary and Secretary and Secretary and Secretary and Secretary and Secretary and inematic dipoles adree with each results from this work at the bottom. estimator. As such, the performance of the Poisson-rms estimator still NVSS (blue), RACS (red), RACS with rms power law (green), and NASK: CISTINGUISH CLUSTEMIL CIL star). Diেerent transparency levels represent 1, 2, and 3 uncertain-levels represent 1, 3, and 3 uncertain-leve
District transparency levels represent 1, 3, and 3 uncertain-levels representation-levels representation-level <u>demonstrate that different kin</u> *N*side = 32 and *N*side = 64. Task: **distinguish clustering dipole from kinematic dipole** and shown in Table 3. The noise variation of the simulated catalogue catalogue catalogue catalogue catalogue catalogue matic dipoles adree with each d in this case means that the representation of the representation \mathcal{L} **demonstrate that different kinematic dipoles agree with each other**

map and ²/d.o.f. = 1.49 for the *N*side = 64 map, but ²/d.o.f. val-Wagenveld et al. 2023

Nature of primordial perturbations

Cosmological inflation

(early epoch of accelerated expansion) implies the existence of almost **scale invariant** and close to **Gaussian** primordial fluctuations of matter and space time

Two realisations of a Gaussian δ and a non-Gaussian $\delta+\delta^2$ distribution

-0.2 0.0 0.2 0.4 0.00 0.01 0.02 0.03 0.04 -0.2 0.0 0.2 0.4 0.00 0.01 0.02 0.03 0.04 realisation 1 $\mu = 0, \sigma = 0.1$ pdf pdf **Fighting Fighting realisation 2** $\mu = 0, \sigma = 0.1$

Nature of primordial perturbations

Cosmological inflation

The minimally expected non-Gaussian effects are tiny The examples show $f_{\rm nl} \thicksim 1$ for 10 000 draws and $\delta = \mathcal{O}(0.1)$ and $\mathcal{O}(0.01)$

Two realisations of a Gaussian δ and a non-Gaussian $\delta+\delta^2$ distribution

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-0.02 0.00 0.02 0.04 0.00 0.01 0.02 0.03 0.04 -0.02 0.00 0.02 0.04 0.00 0.01 0.02 0.03 0.04 pdf pdf and **Fighting Contract of Telecom** realisation 2 $\mu = 0, \sigma = 0.01$ realisation 1 $\mu = 0, \sigma = 0.01$

So far, all observations agree with Gaussianity

Nature of primordial perturbations

- Boost of power at largest scales due to influence of non-Gaussianity on halo bias Matarese et al. 2000, Dalal et al 2008, Matarese & Verde 2008, Slosar et al. 2008
- multi-tracer technique to reduce cosmic variance Seljak 2009
- Several forcasts for SKA-MID Raccanelli et al. 2012, Ferramacho et al. 2014, Alonso & Ferreira 2015, Raccanelli et al. 2018, Gomes et al. 2020 claim that $f_{\rm nl} \sim 5$ could be reached Ferramacho et al. 2014
- Assumptions should be updated

Radio luminosity functions Figure 2. *Left:* The re-calculated galaxy RLFs (dotted lines) for the smaller area considered here, compared with previously published RLFs (solid lines). *Middle:* RLFs calculated by process rather than galaxy. *Right top:* RLFs calculated here by galaxy classifications

- Process based (surface brightness) compared to galaxy morphology based radio luminosity function of SFGs and AGNs from LOFAR international baselines deep fields
- Shows that AGN luminosity has been underestimated (up to factors of 2) and SFG slightly overestimated
- Impact on differential source counts, redshift distribution and bias needs to be further investigated

Figure 3. The Rufa panels (top panels) and Rufa (contract al. submitted

Late time accelerated expansion leads to late time **integrated Sachs-Wolfe effect**

Probes LCDM and other dark energy models

Yet, only weak significance (2.6*σ*/2.8*σ*) for ISW from CMB-radio (NVSS/RACS-low), but these are still the largest non-CMB ISW signals Planck 2016, Bahr-Kalus et al. 2022 In LoTSS DR2 less than 2*σ* (wide area is essential) Nakonecny et al. 2024

Nature of dark energy (2.0 mJy, *S*/*N* > 5.0) HALOFIT 0.82⁺0.⁰⁸

SKA-MID Array Assembly

150 km baseline of AA* does not look good

uv coverage of AA* - SKA008 for 4h track at 1.4 GHz uv coverage after adding single Which goals can be achieved with such a lower angular resolution — harder to get good multi-wavelength cross identification— go to higher frequencies — but not of interest for HI

Cosmology with SKA

- Target fundamental questions
- Unique opportunities at large and ultra-large cosmological scales due to combination of sensitivity and survey speed (and angular resolution AA4)
- Cosmic dipoles (and other higher multipoles) -> Cosmological principle
- Non-Gaussianity -> Quantum fluctuations and non-linear structure
- Integrated Sachs-Wolfe -> Dark energy
- All need to cover largest anglar scales at several bands and photo-z

CMB dipole

 T_1 is measured most precisely by Planck better than monopole T₀

COBE-DMR map

$\Delta T = 3.353$ mK

Assumed to be due to motion of Sun w.r.t. cosmic 2.7 K background radiation

• Solar dipole (10-3) (Stewart & Sciama 1967, **Doppler boost & aberration**

- Galactic forgrounds contaminants (10-3)
- **•** Annual kinematic dipole (10-4)

Other probes of the rest frame

Radio and quasar dipoles

Use counts-in-cell from wide area surveys Ellis & Baldwin 1984

> α (z) from LoLSS cross-matched with other radio surveys and photo-z from LoTSS VAC Böhme et al. 2023

$$
\frac{dN}{d\Omega}(>S,\mathbf{e}) = \frac{dN}{d\Omega}(\geq S) (1 + \mathbf{d} \cdot \mathbf{e} + \ldots),
$$

$$
d = [2 + x(1 - \alpha)]v/c, \quad S \propto \nu^{\alpha},
$$

More complicated if x AND α evolve with z Chen & Schwarz 2016, Nadolny et al. 2021, Dalang & Bonvin 2022, von Hausegger 2024 No indication for evolution of *α* (for radio galaxies), but huge scatter

d*N* dΩ ∝ *S*−*^x*

Radio and quasar dipoles **TAC**

Photometry and calibration (do we know the flux densities at required accuracy and precission?)

Estimators and masks (Siewert et al. 2021, Dam et al. 2022, Böhme et al. in prep.)

Evolution effects (Dalang & Bonvin 2022, Guandalin et al. 2022, von Hausegger 2024)

Clustering Dipole (Rubart et al. 2014, Bengaly et al. 2019, Dam et al. 2022, Wagenveld et al. in prep.)

Task: **distinguish clustering dipole from kinematic dipole** and

demonstrate that different kinematic dipoles agree with each other Böhme et al. in prep. \bigcap \mathbb{Z} and FIG. 1: Maps (rows (a) and (c)) and histograms (rows (b) and (d)) of counts-in-cells and corresponding best-fit Poisson and negative binomial distribution. The corresponding Chi-square values and flux density cuts can be found

Other probes for kinematic dipole **Supernovae Ia**

Can be degenerate with large scale bulk flows $\mu(z, e) = \mu_{com}(z) + 5 \log_{10}(1 - e \cdot v/c)$

SN1a magnitude is coherently modulated by proper motion of Solar system Sasaki 1985, Horstmann et al. 2022

Agreement!

But see also Sorrenti et al. 2022 they find larger velocity and a tension in dipole direction for Pantheon+ sample (but Pantheon+ contains more local and less high-z SNe)

