Cosmic Dipole Tensions: Confronting Planck, NVSS, RACS and CatWISE

CosmoVerse@Istanbul 2025

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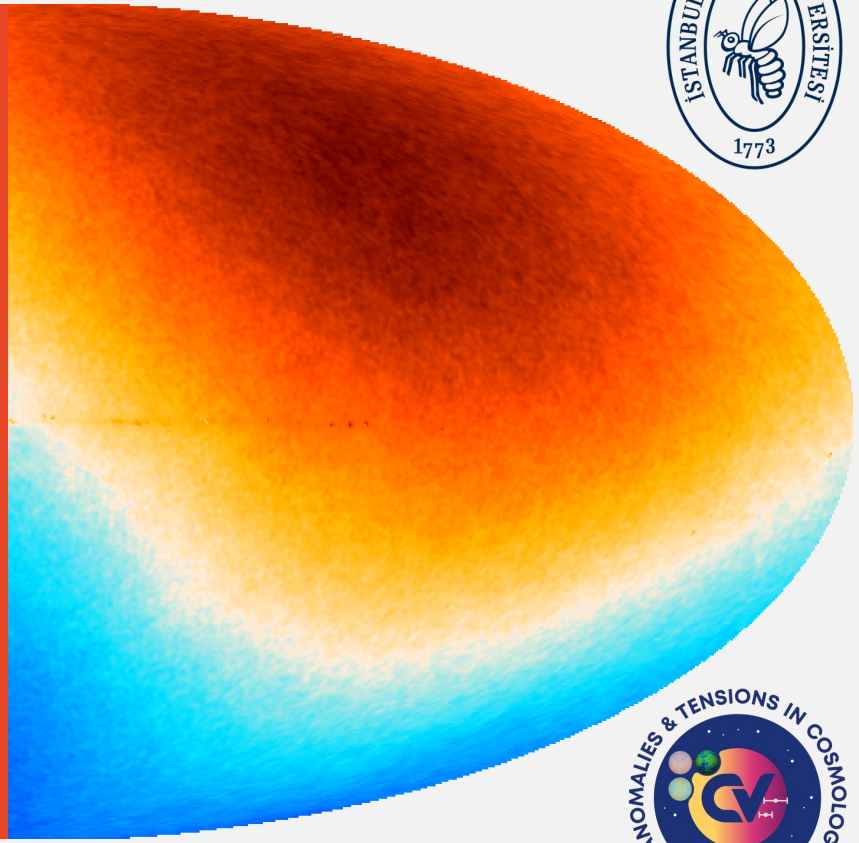
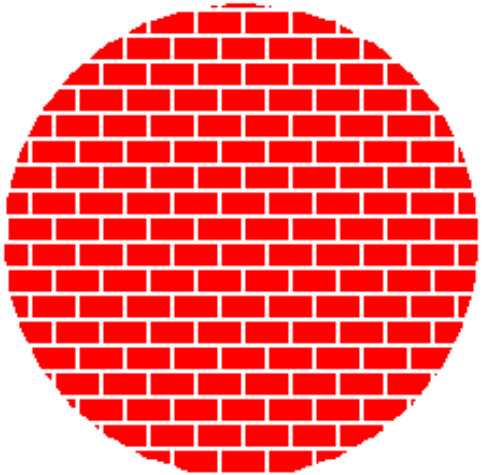
Supervised by Geraint F. Lewis and Tara Murphy

THE UNIVERSITY OF SYDNEY

Celebrating 175 years

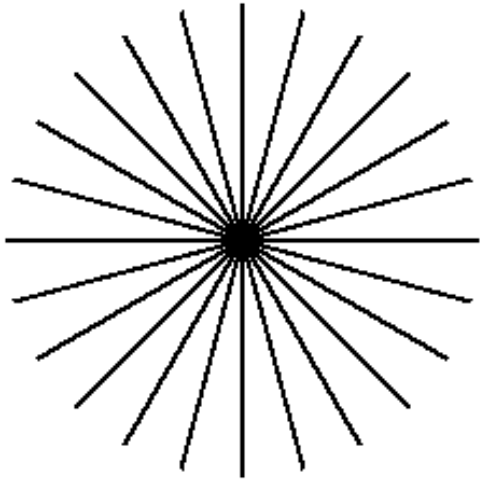


The Cosmological Principle: a big assumption



Universe is **homogeneous**

(same everywhere)



Universe is **isotropic**

(same in all directions)

Image credit: Edward L. Wright

The Cosmological Principle: important in ΛCDM

- Assumed in the Friedmann–Lemaître–Robertson–Walker spacetime

- Therefore, assumed in the standard concordance model of cosmology, ΛCDM

The Cosmological Principle: important in ΛCDM

- Assumed in the Friedmann–Lemaître–Robertson–Walker spacetime
- Therefore, assumed in the standard concordance model of cosmology, ΛCDM
- If the Cosmological Principle **breaks**, all the stones come **tumbling to the ground**…

We must continue to **interrogate the CP** and its **evidence**.

The Cosmic Microwave Background: very smooth map

(CMB)

$\Delta T/T \approx 10^{-5}$

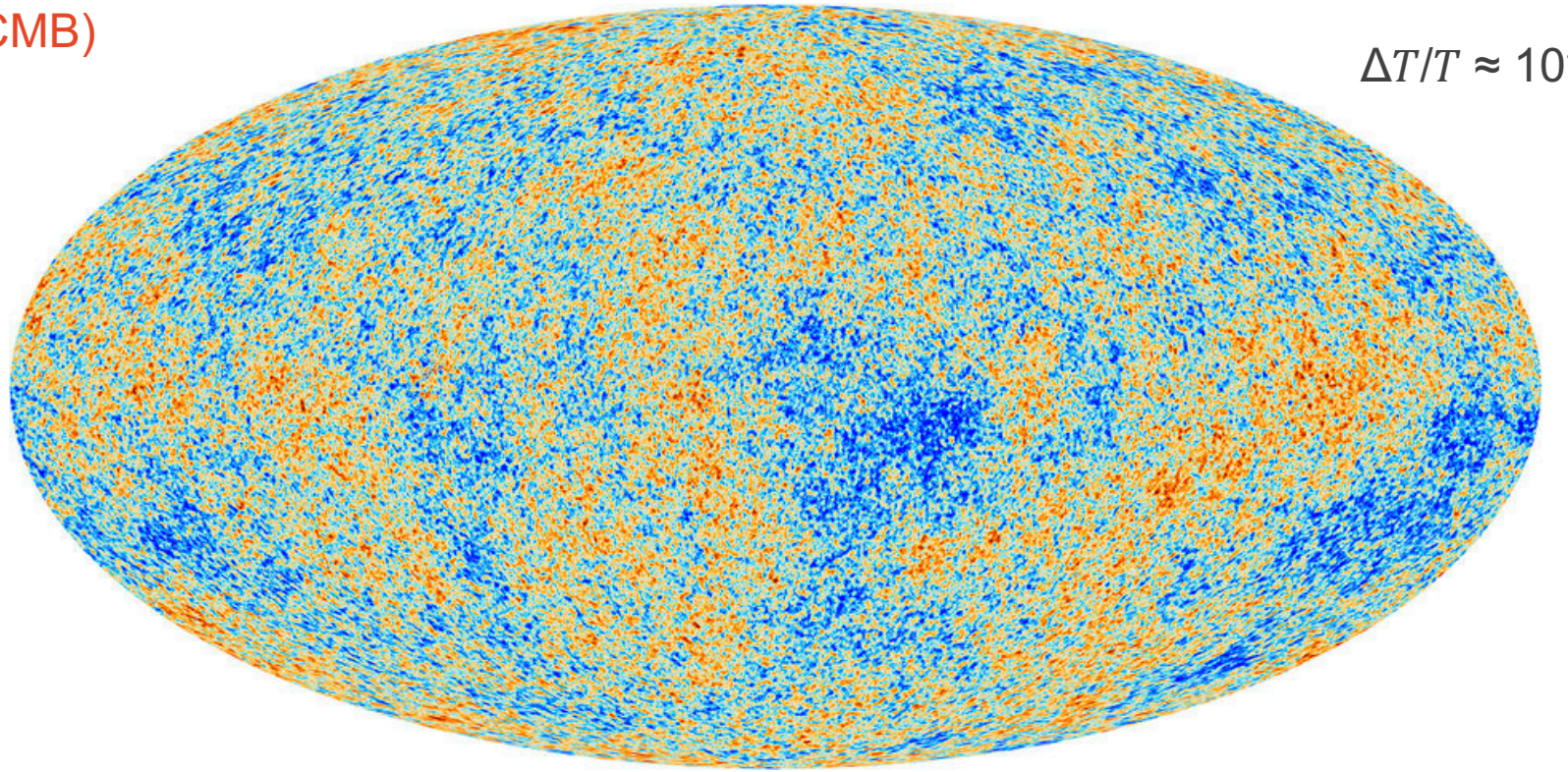
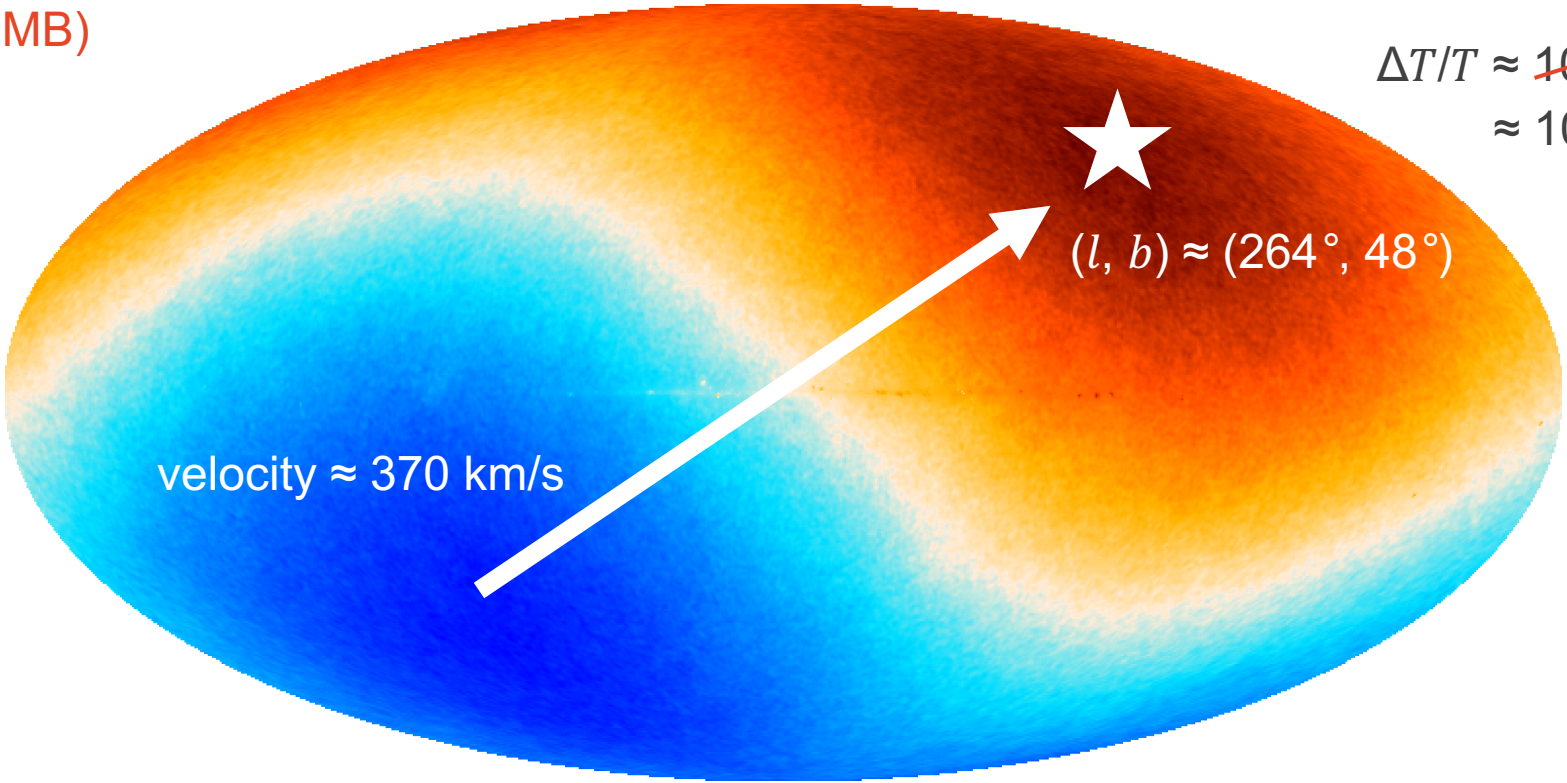


Image credit: *Planck*

The Cosmic Microwave Background: temperature **dipole**

(CMB)



Relativistic aberration

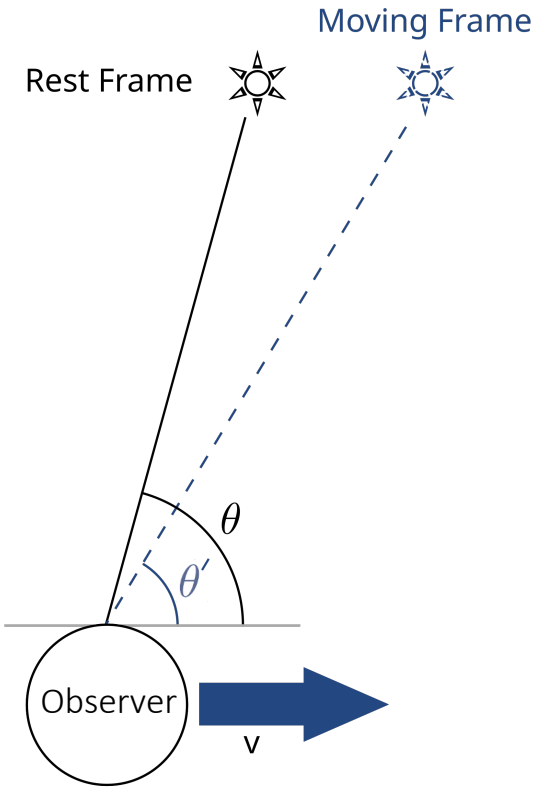


Image credit: Wikipedia

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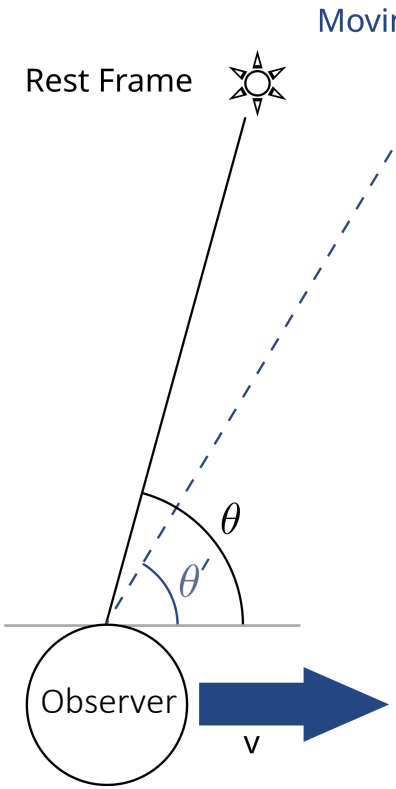

Sky divided into **equal** angular-area **pixels**

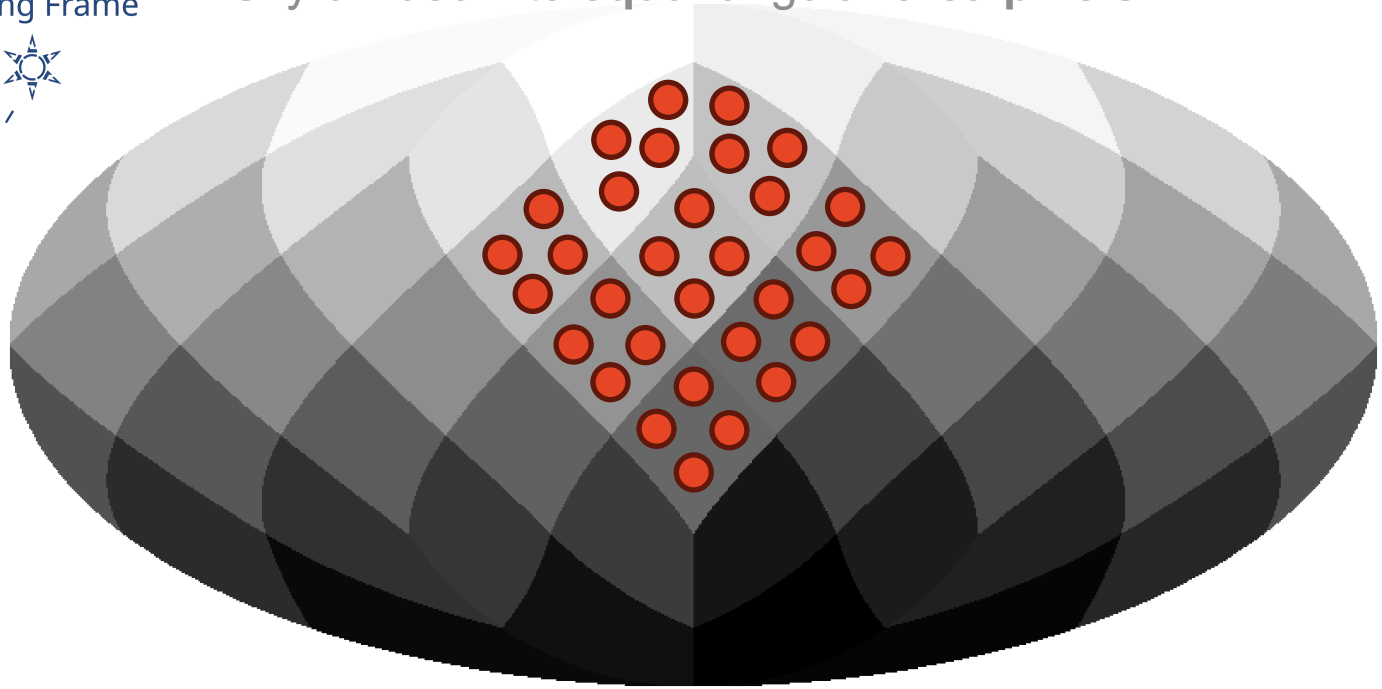

Image credit: Wikipedia

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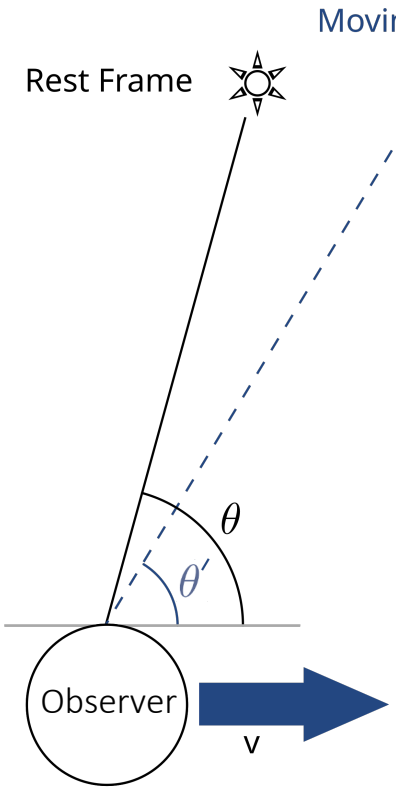

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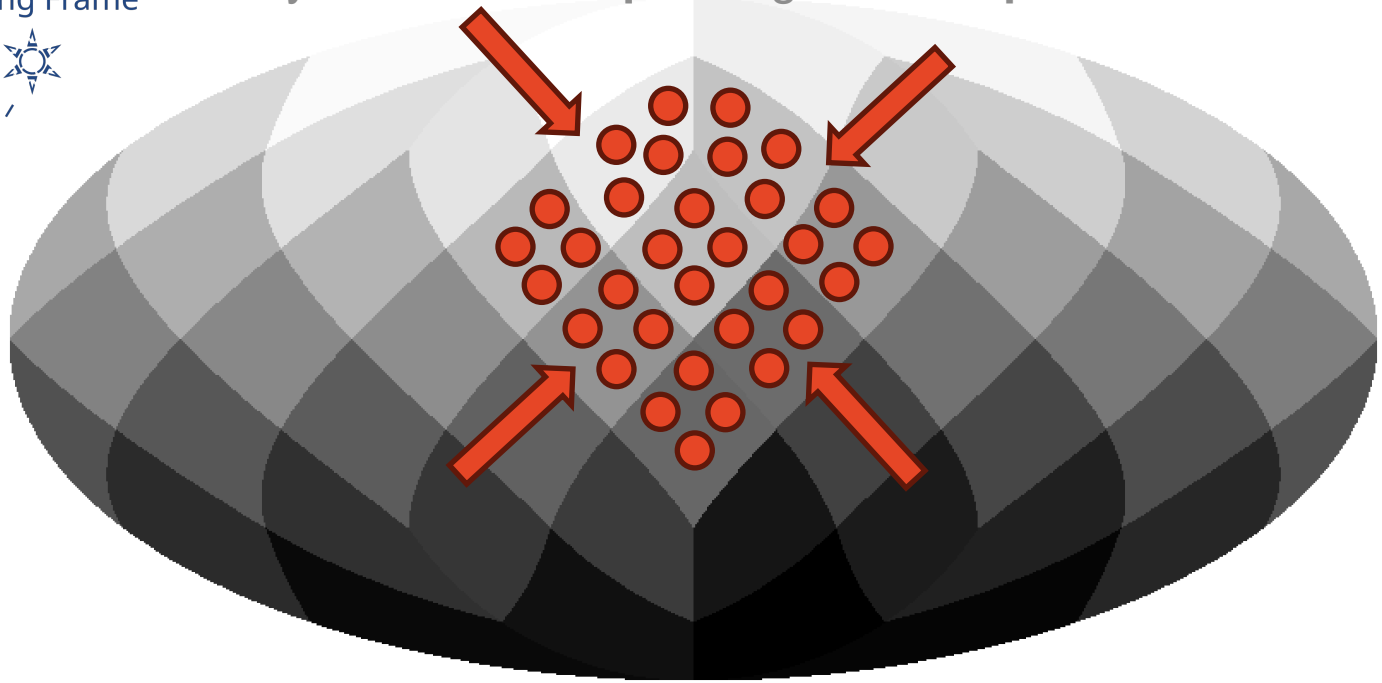
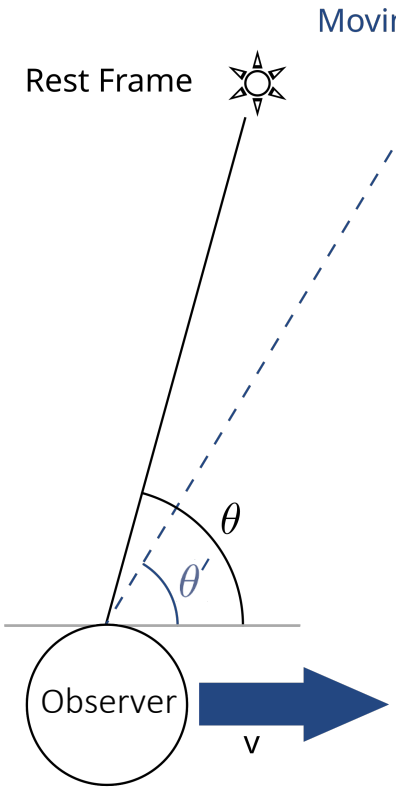


Source **density increases** due to motion

Image credit: Wikipedia

Relativistic aberration



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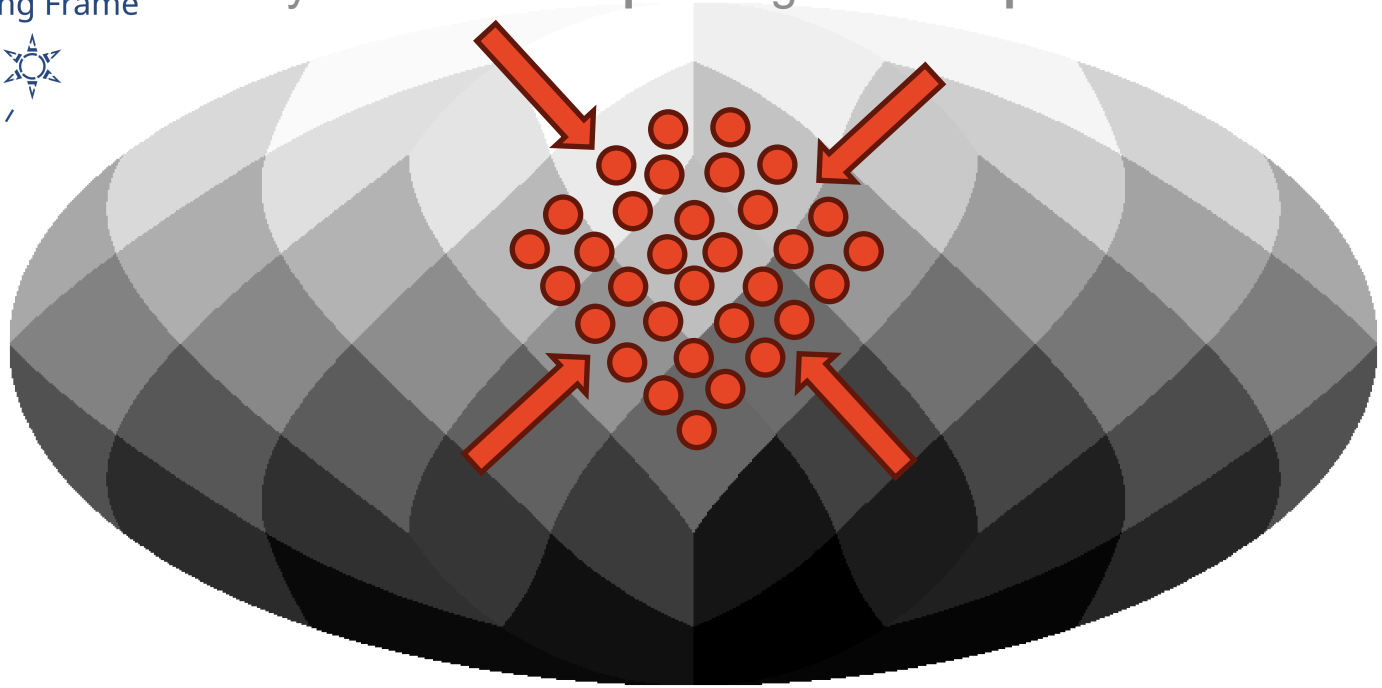

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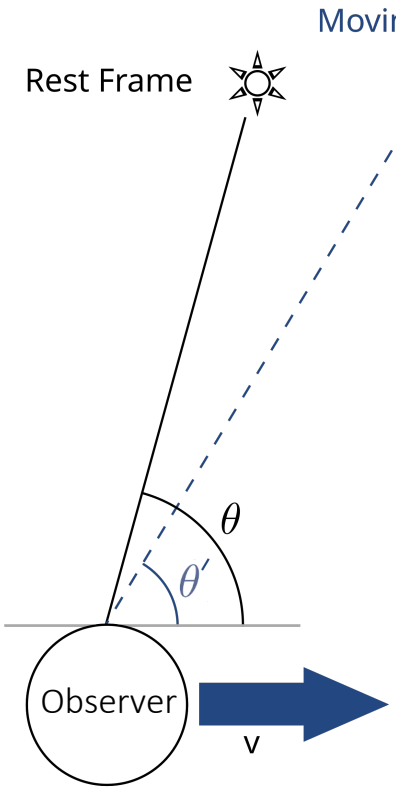

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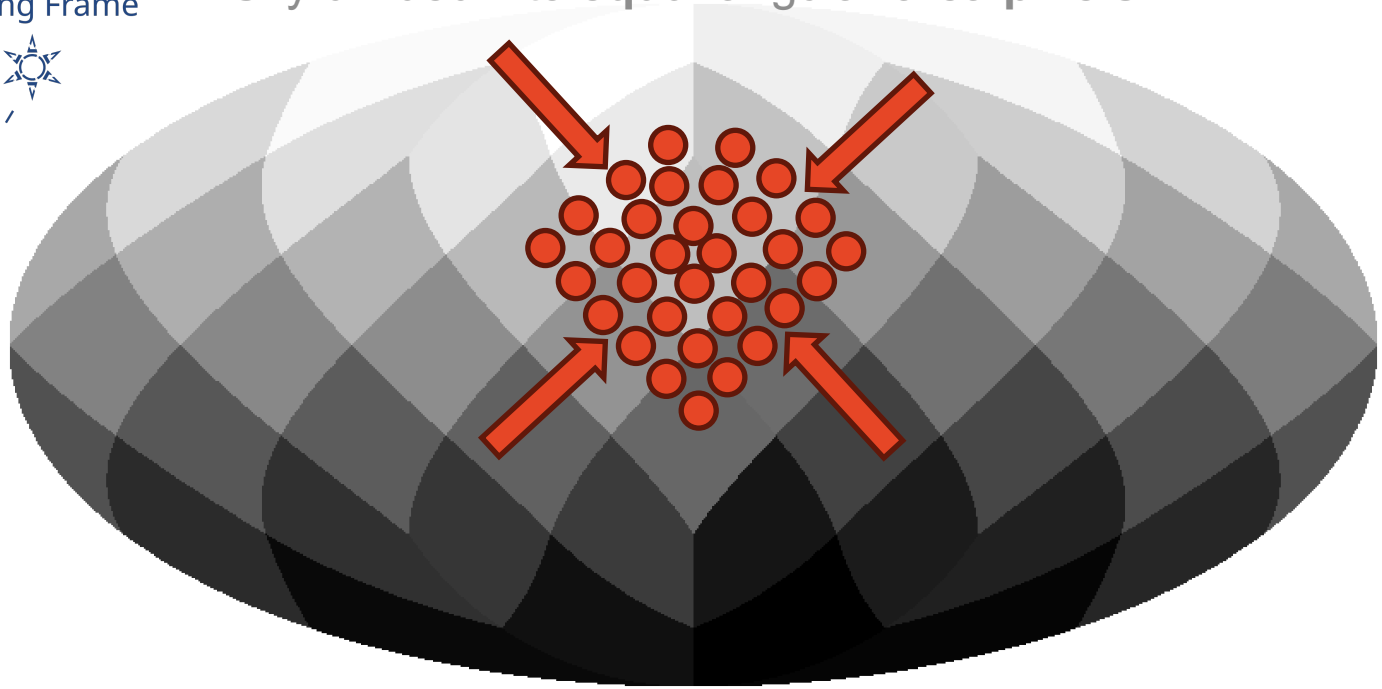
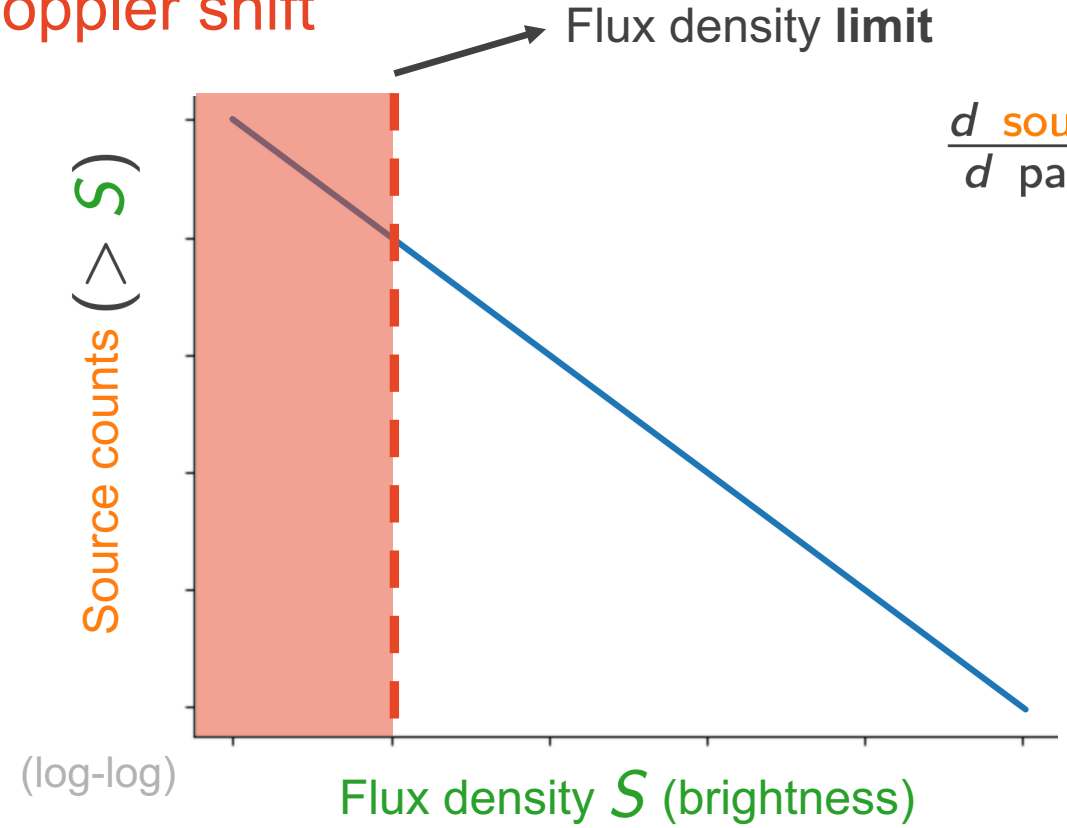


Source **density increases** due to motion

Image credit: Wikipedia

Doppler shift



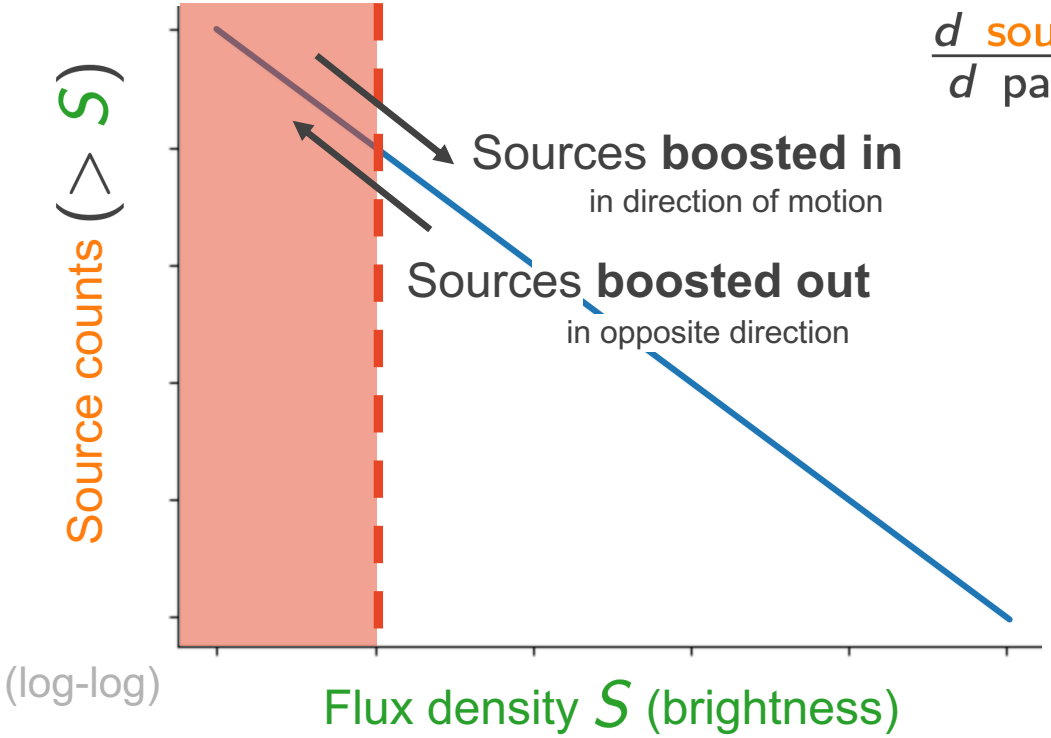
$$\frac{d \text{ source counts}}{d \text{ patch of sky}}(>S) \propto S^{-x}$$

$$S \propto f^{-\alpha}$$

Flux density **changes** with frequency f

Ellis G. F. R., Baldwin J. E., 1984, MNRAS, 206, 377

Doppler shift



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Flux density **changes** with frequency f

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The dipole modulation

$$D = (2 + \underbrace{x[1 + \alpha]}_{\text{Doppler}})(v/c)$$

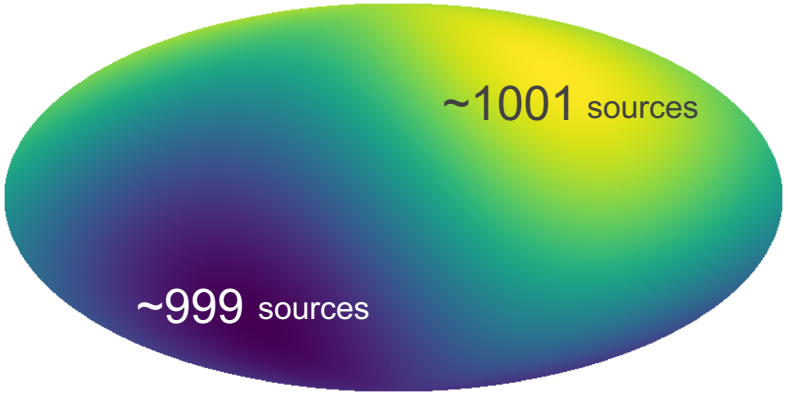
2: Aberration

Ellis G. F. R., Baldwin J. E., 1984, MNRAS, 206, 377

The dipole modulation

$$D = (2 + x[1 + \alpha])(v/c)$$

Aberration — Doppler



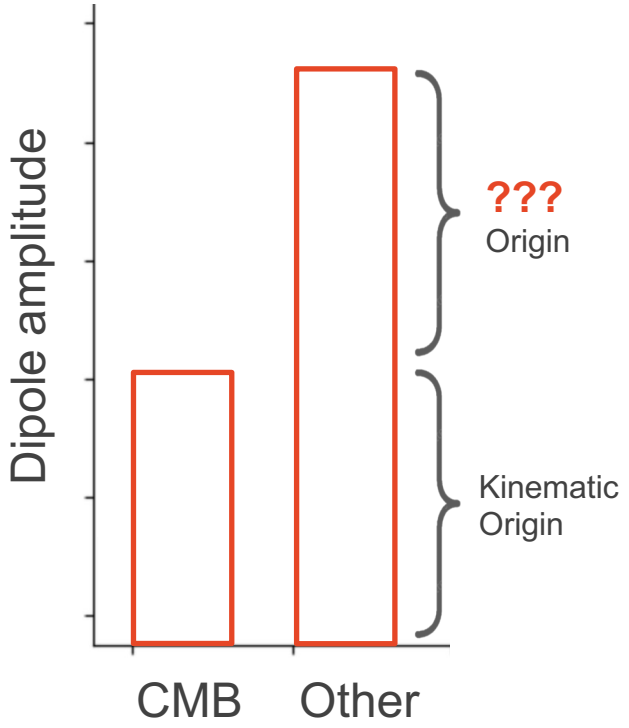
This is a small effect, modulation of **around 0.1% over the sky**

Average 1000 sources/pixel with **amplitude** $D \sim 0.001$

Ellis G. F. R., Baldwin J. E., 1984, MNRAS, 206, 377

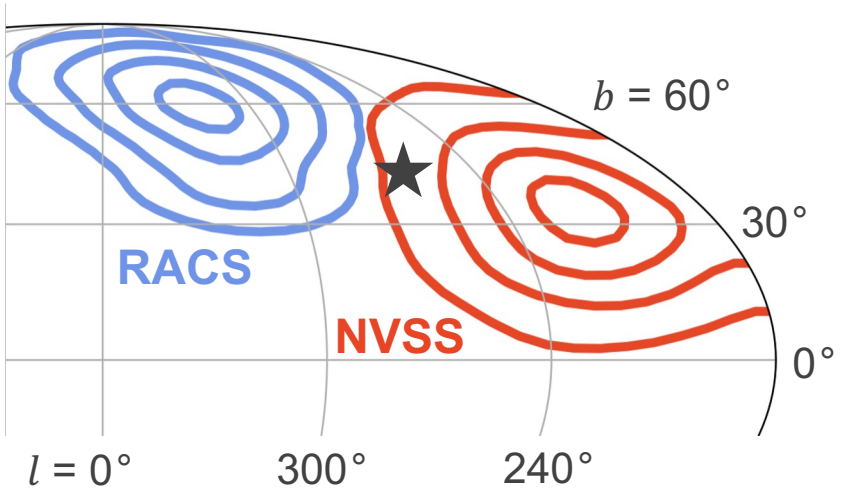
Recap: How does this relate to cosmology?

- Can **measure** dipole in survey (e.g. galaxies)
- If dipole **disagrees** with CMB, this indicates an **anisotropy**
- Anisotropy violates the **Cosmological Principle**



What dipoles have been found?

Dipole **directions**:
- Generally **agree** with the CMB



(0.5σ contours)

Dipole **amplitudes**:
- Consistently **exceed** the CMB amplitude

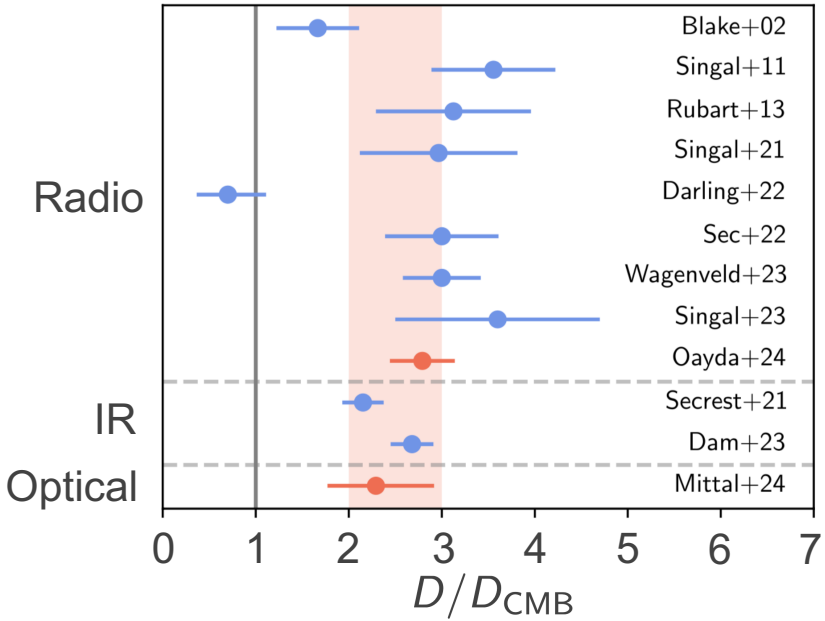
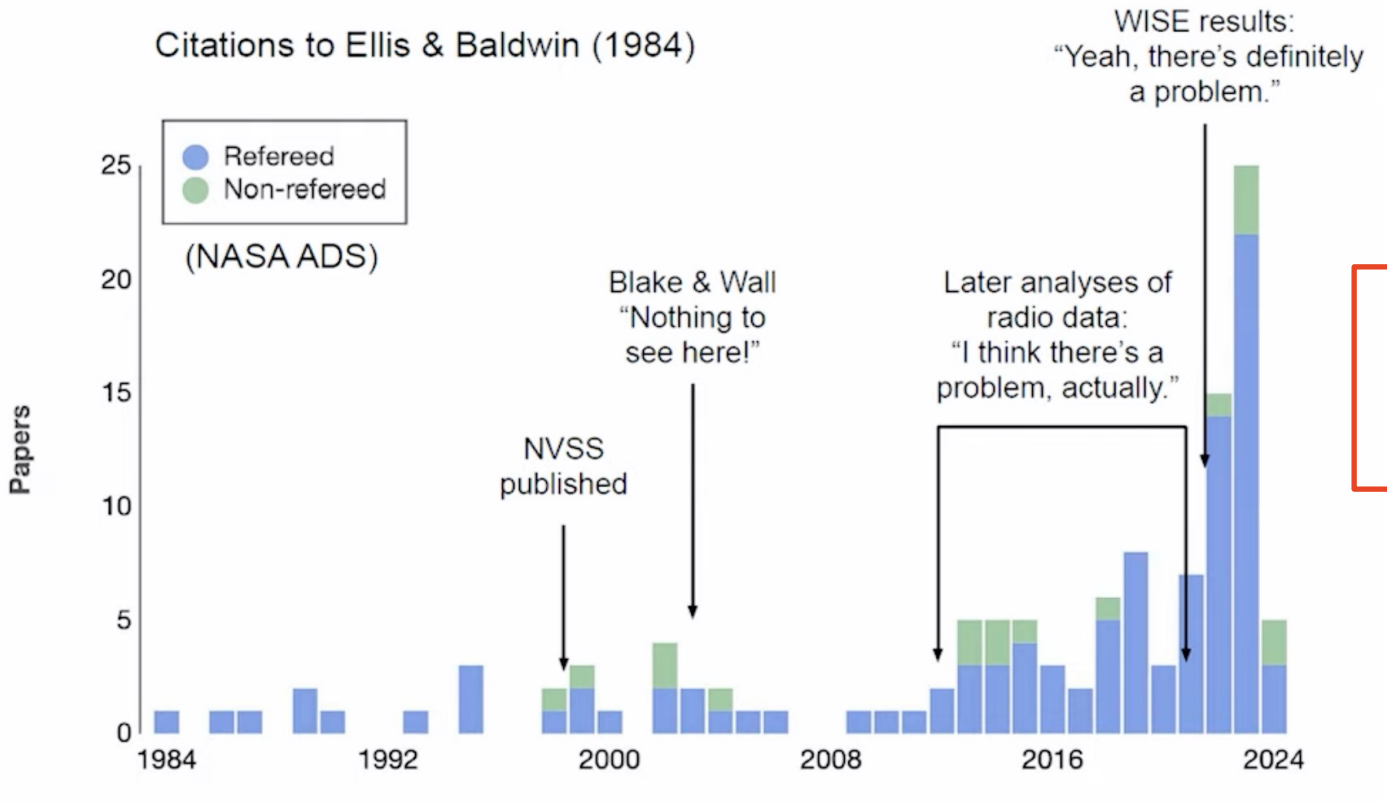


Image credit: Oayda et al. (2025; in prep)

Houston, we have a problem



Poses a **serious challenge** to the CP and the **standard model**.

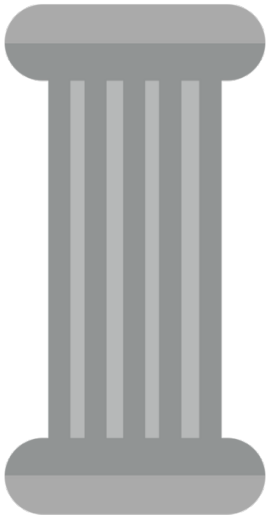
Measurements now **disagree** with the CMB at **>5σ**.

This is **comparable** to the **Hubble** tension.

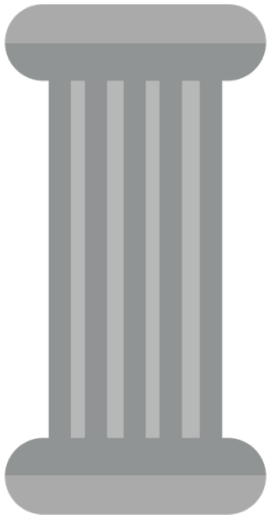
Image credit: Nathan Secrest

Three pillars of tension

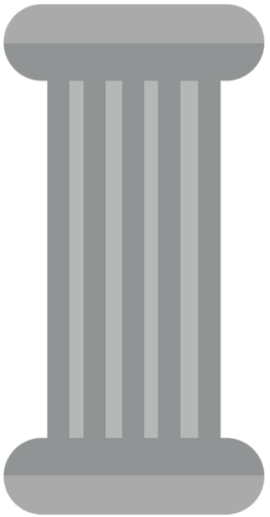
Tension between **parameters**



Tension between **models**



Tension between **datasets**



Three pillars of tension

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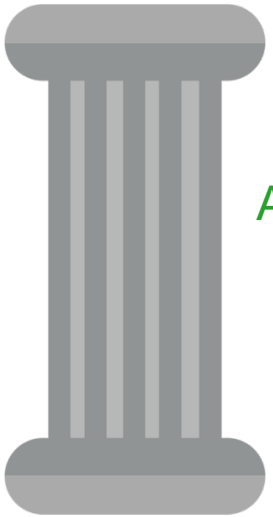

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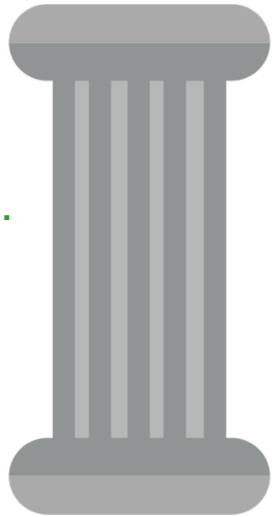
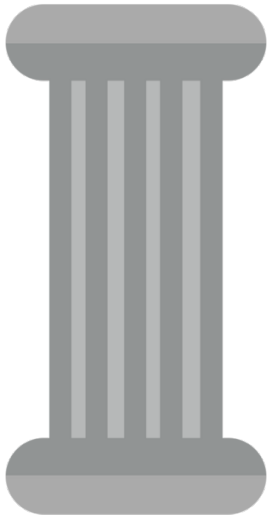


Already done.

We do this **here**.

Tension between **datasets**



Tension between datasets: R-statistic

- **Bayesian evidence** $\mathcal{Z}_D$ is the **probability** of observing the data D

Concordance:

$$R \gg 1$$

$$\mathcal{Z}_{AB} \gg \mathcal{Z}_A \mathcal{Z}_B$$

Combining datasets **increases** confidence

$$R = \frac{\mathcal{Z}_{AB}}{\mathcal{Z}_A \mathcal{Z}_B}$$

Tension:

$$R \ll 1$$

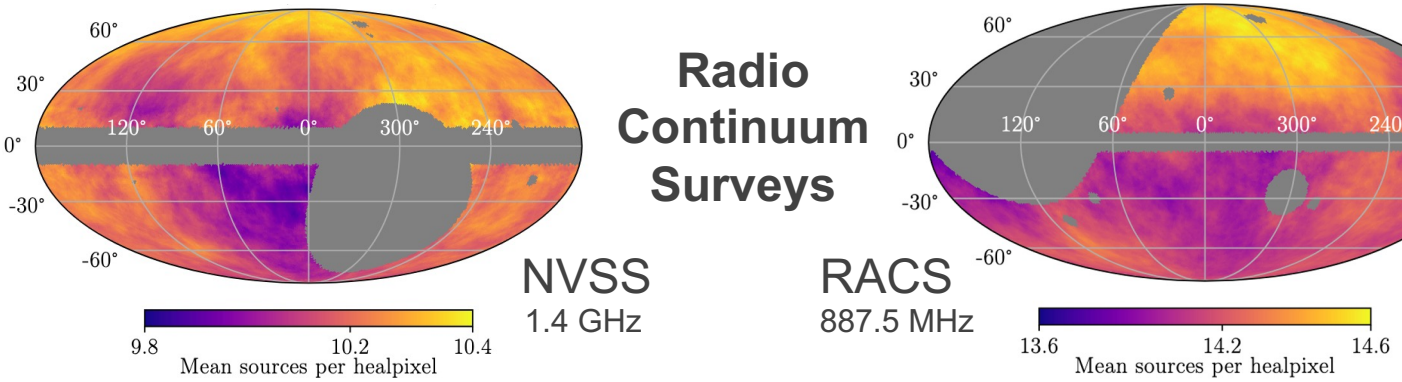
$$\mathcal{Z}_{AB} \ll \mathcal{Z}_A \mathcal{Z}_B$$

Combining datasets **decreases** confidence

Can convert R to **σ-level tension**

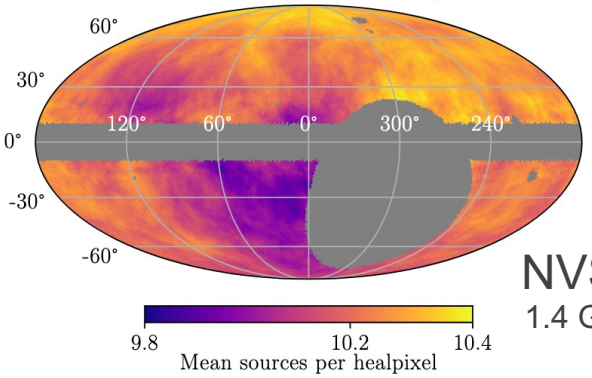
Marshall P., Rajguru N., Slosar A. c. v., 2006, Phys. Rev. D, 73, 067302

Surveys of interest…

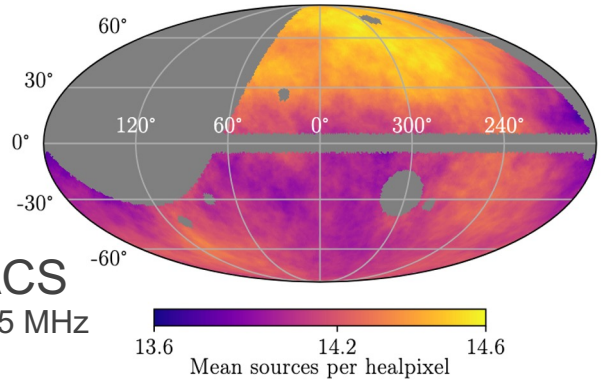


NB: Radio/IR projections are box-car smoothed within 1sr

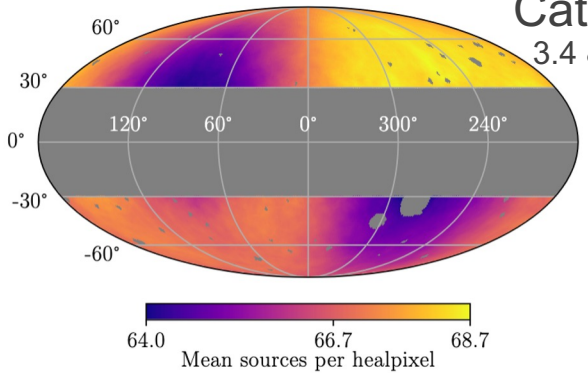
Surveys of interest…



NVSS
1.4 GHz

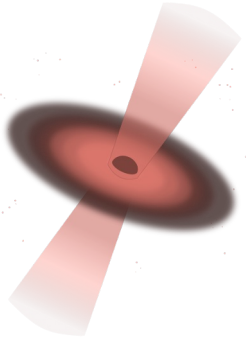


RACS
887.5 MHz



CatWISE
3.4 & 4.6 μm

Infrared-selected Quasars



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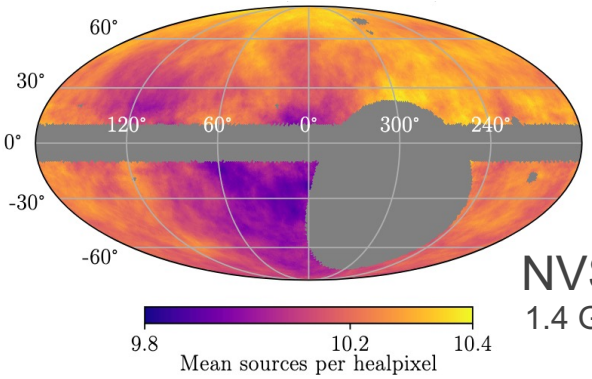
Surveys of interest…



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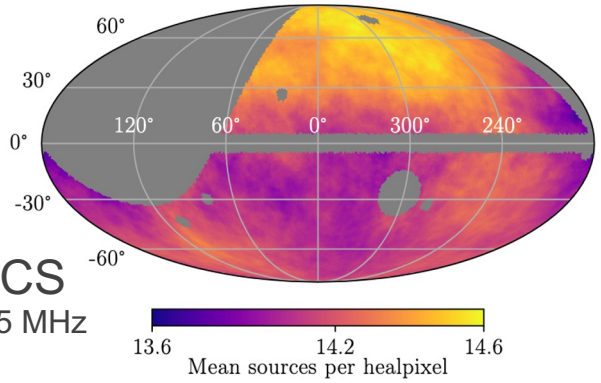

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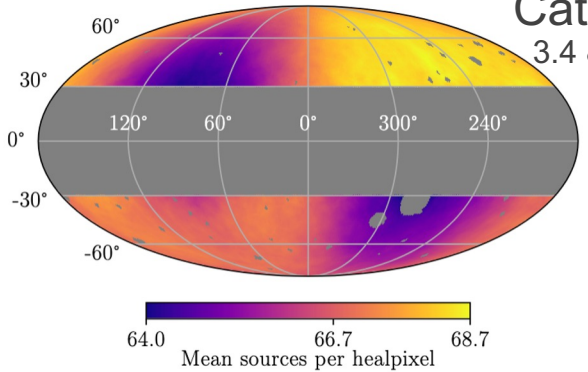

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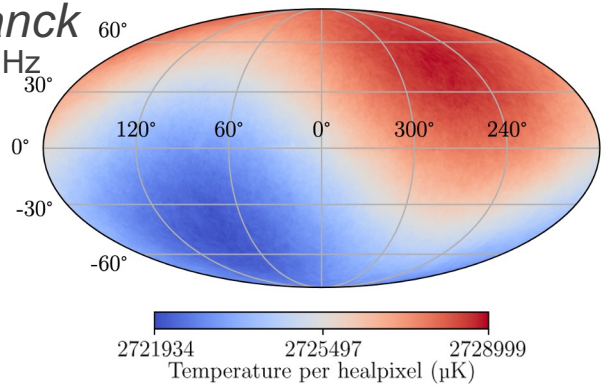

Planck
30 GHz

NB: Radio/IR projections are box-car smoothed within 1sr

The Tension.

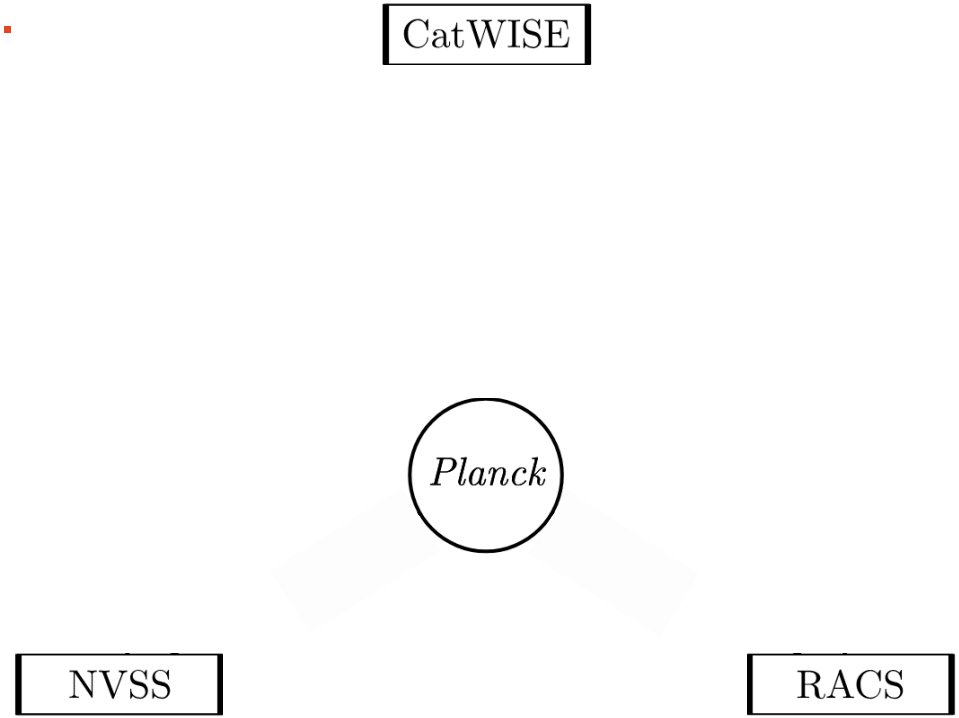

Image credit: Land-Strykowski et al. (2025; submitted)

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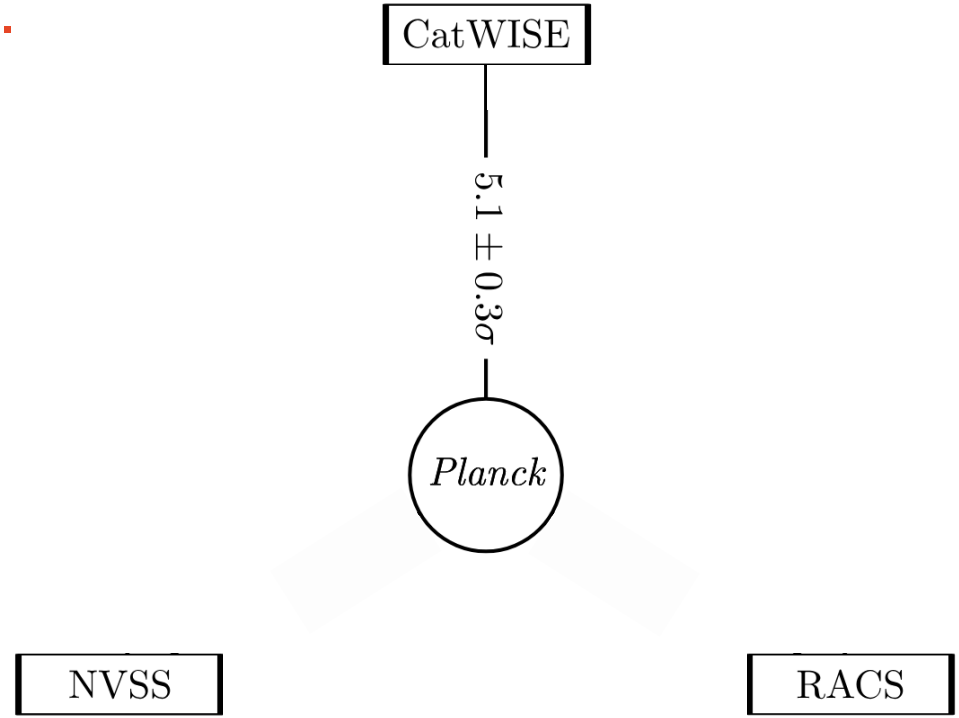

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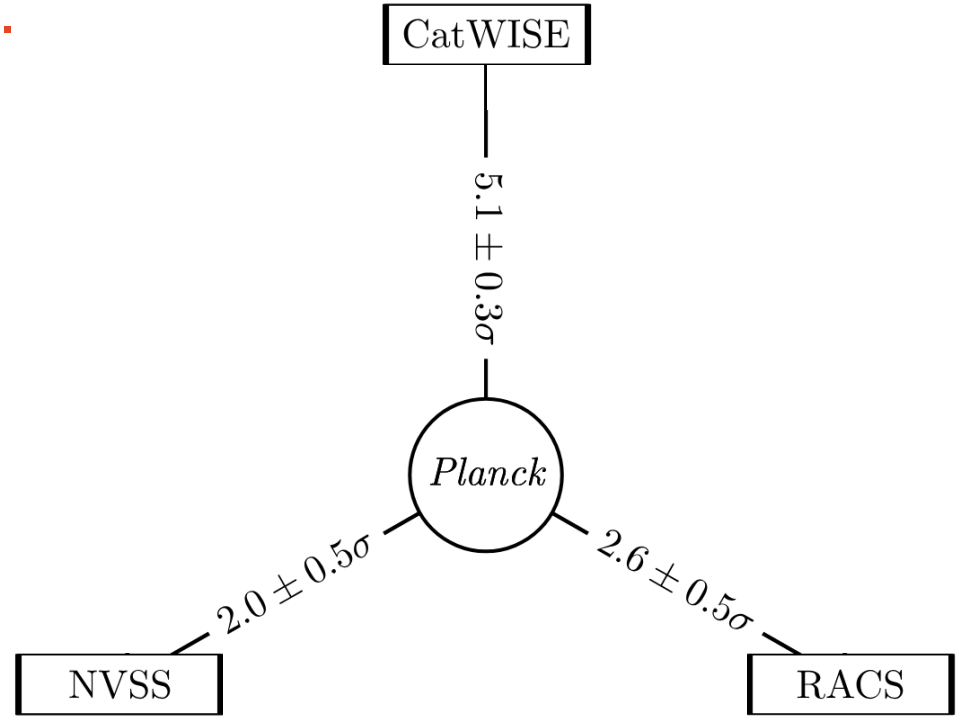

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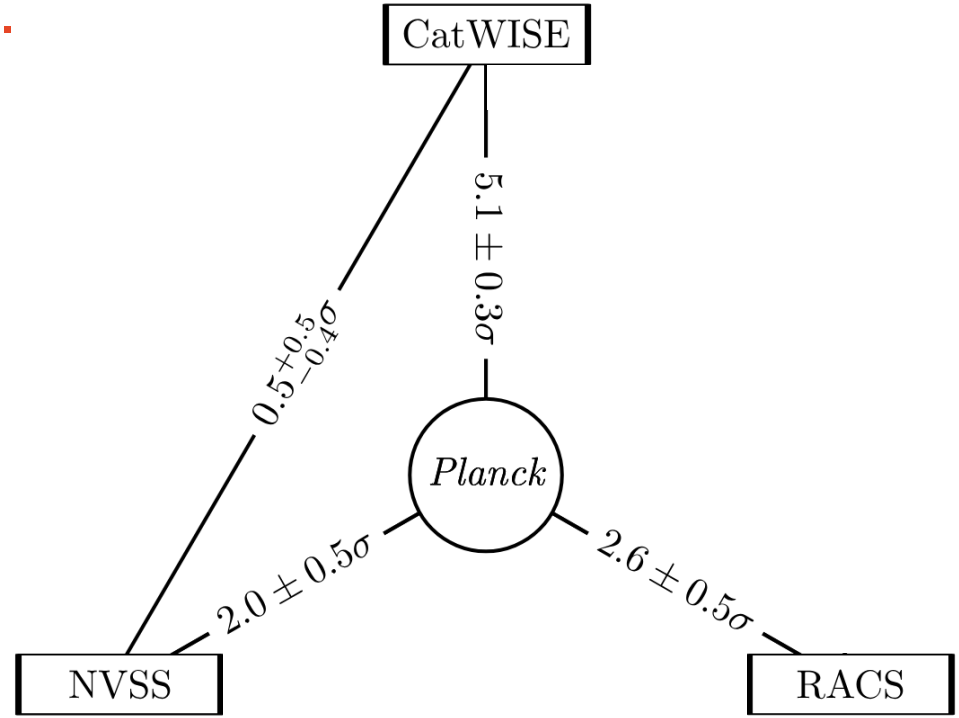

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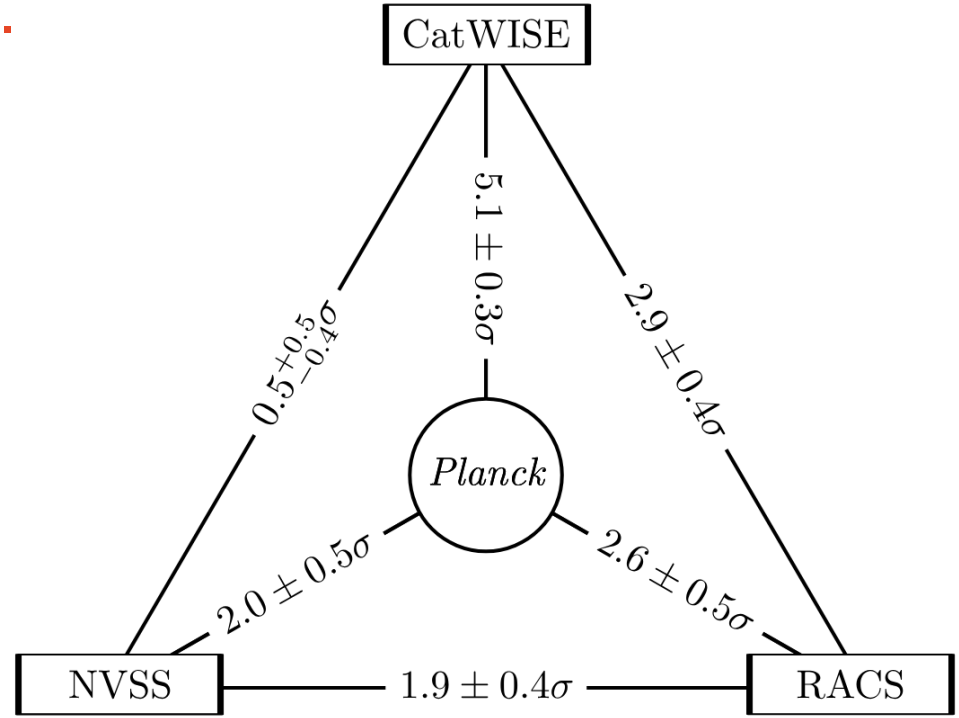


Image credit: Land-Strykowski et al. (2025; submitted)

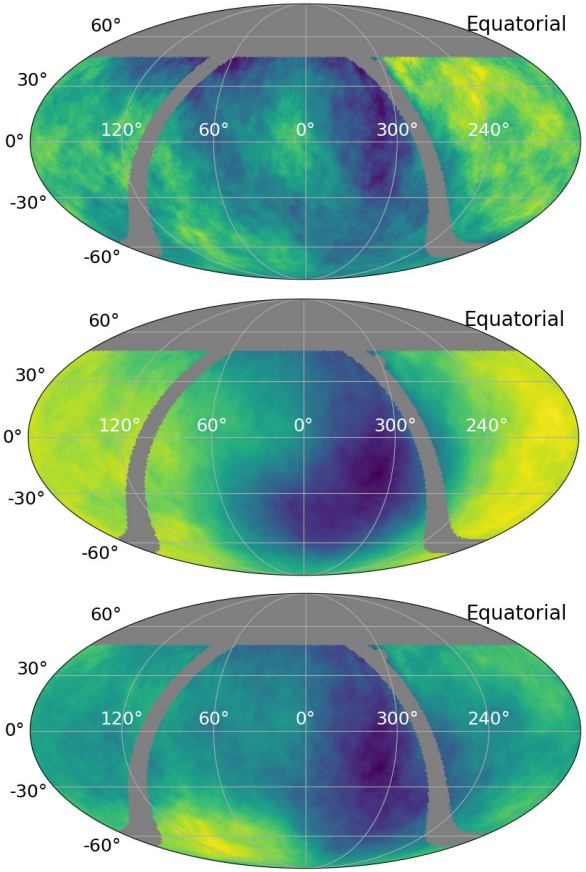
Further investigation: RACS

Inference is **sensitive** to:

- Ionospheric temperature fluctuations and **flux-scaling** compensation

- Choice of **resolution** / convolution

Modelling/understanding these is the **future**.



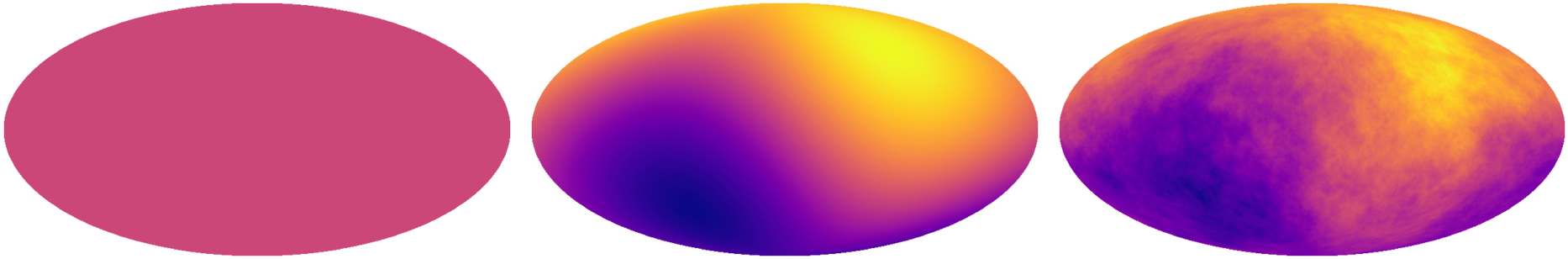
RACS-low2
887.5 MHz

RACS-low3
943.5 MHz
unscaled

RACS-low3
943.5 MHz
scaled

Image credit: Oliver Oayda (2025; private communication)

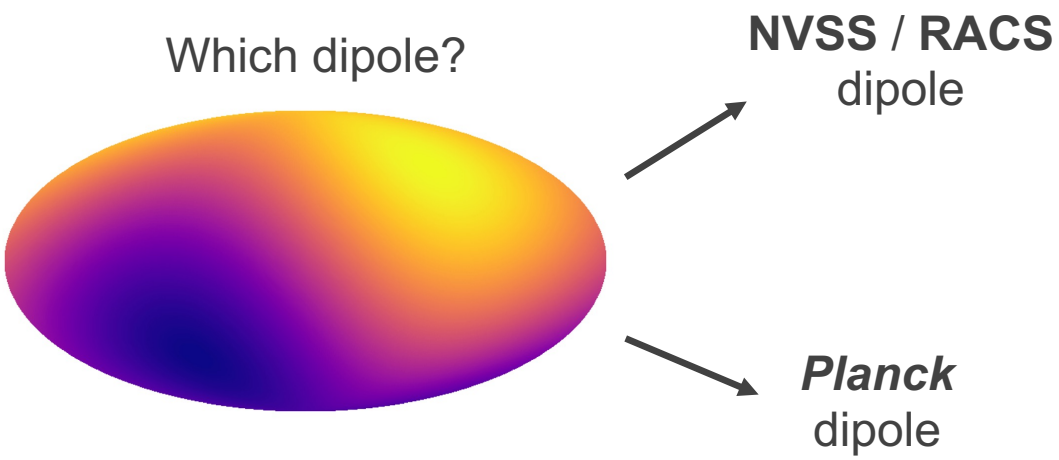
Simulated skies: modulation, information



Homogenous sky → Dipole modulation → Poisson draw

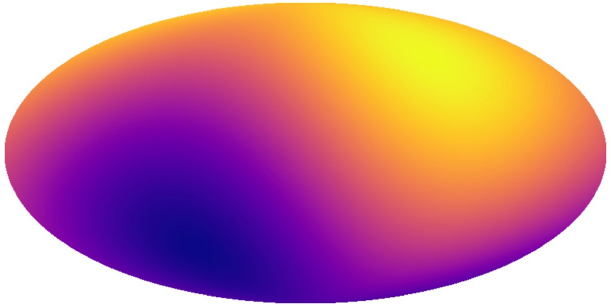
Repeat for **50,000** to **50,000,000** sources

Simulated skies: different dipoles



Simulated skies: different dipoles

Which dipole?



NVSS / RACS dipole vs ***Planck*** data

“Radio continuum dipole”

Planck dipole vs ***Planck*** data

“CMB dipole”

Simulated skies: tension results

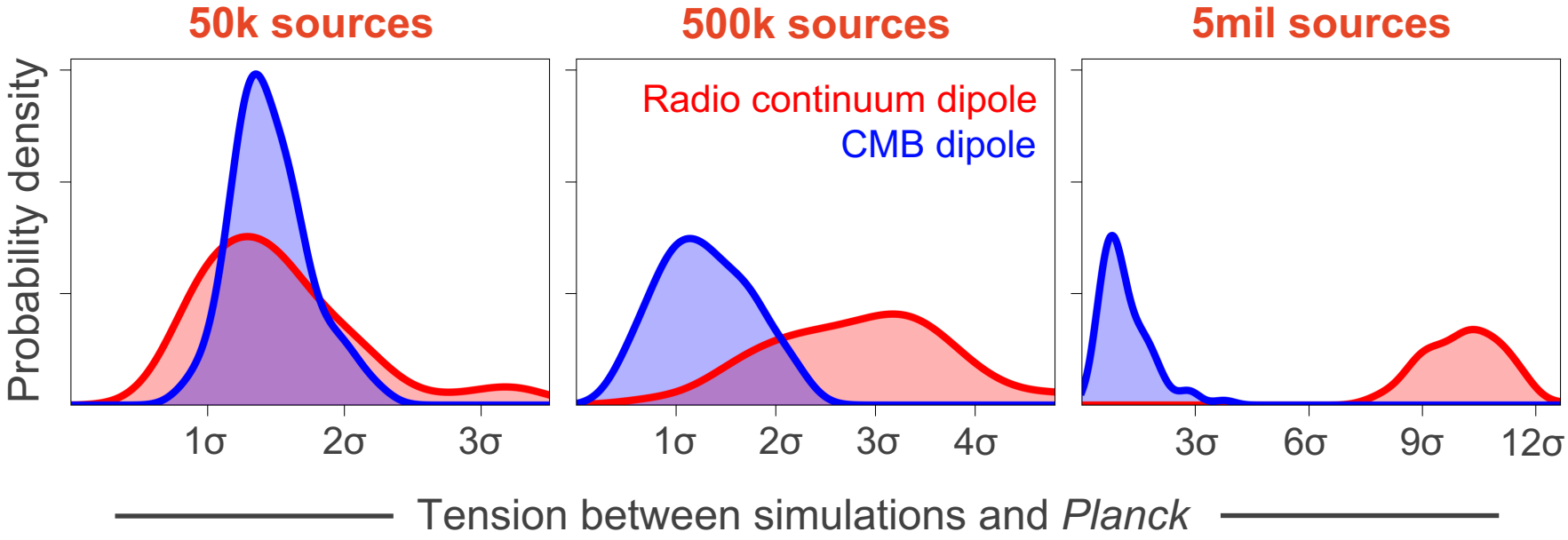


Image credit: Land-Strykowski et al. (2025; submitted)

Simulated skies: tension results

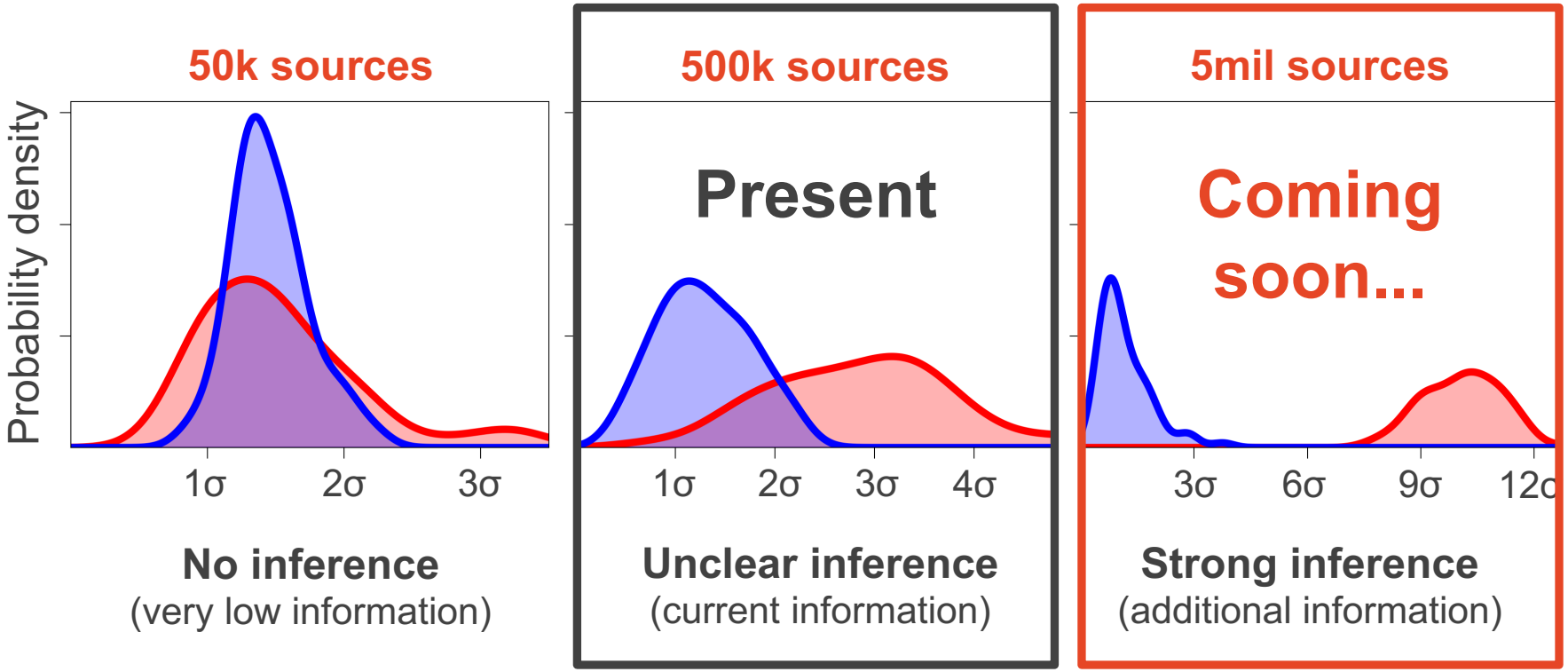


Image credit: Land-Strykowski et al. (2025; submitted)

How many sources do we need?

- **NVSS** dipole ⟶ **5σ** tension with **~1,300,000** sources

- **RACS** dipole ⟶ **5σ** tension with **~1,500,000** sources

Only need **O(10^6)** more sources!!

SKA will observe **5x10^6** and **9x10^8** galaxies

We are on the cusp of untangling the anomaly…

Image credit: Yen-Chi Chen

Change is on the horizon…

- Why homogeneity / isotropy?
- **Inhomogeneous** cosmologies…
  - Dark matter super-void (1−3.4 Gpc)
- **Anisotropic** cosmologies…
  - Tilted cosmology (not Friedmann)
- Or, perhaps, something entirely new…

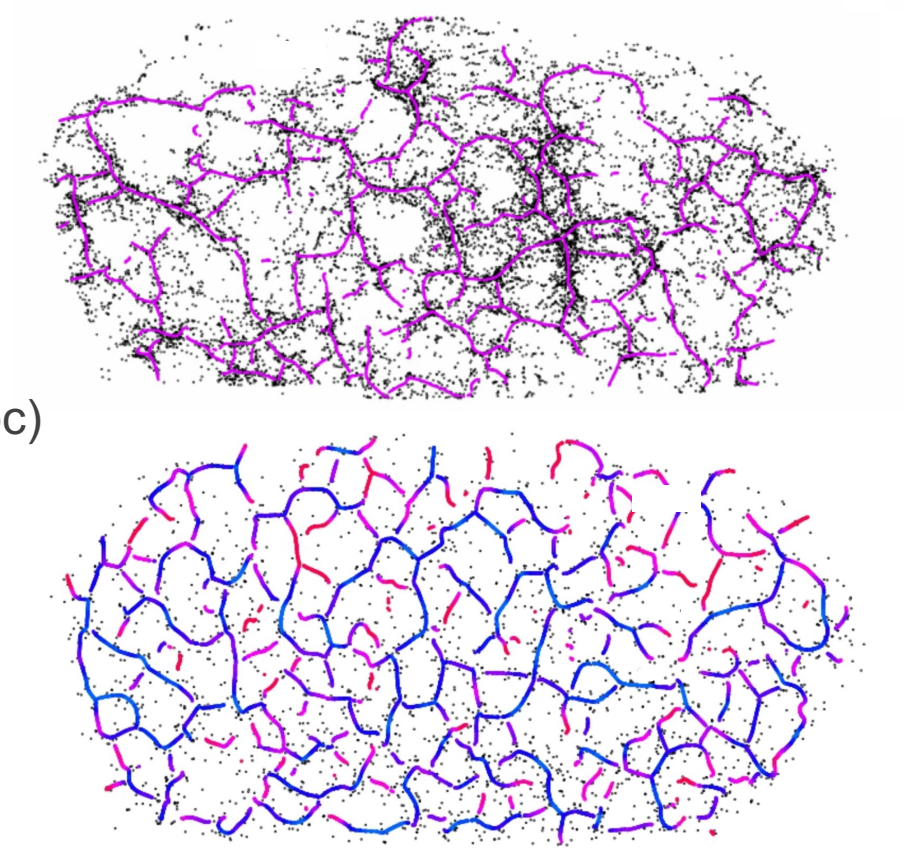


Image credit: Glenn Roberts Jr.

Conclusions

- The **Cosmic Dipole tension** appears to be one of the **most significant** tensions.

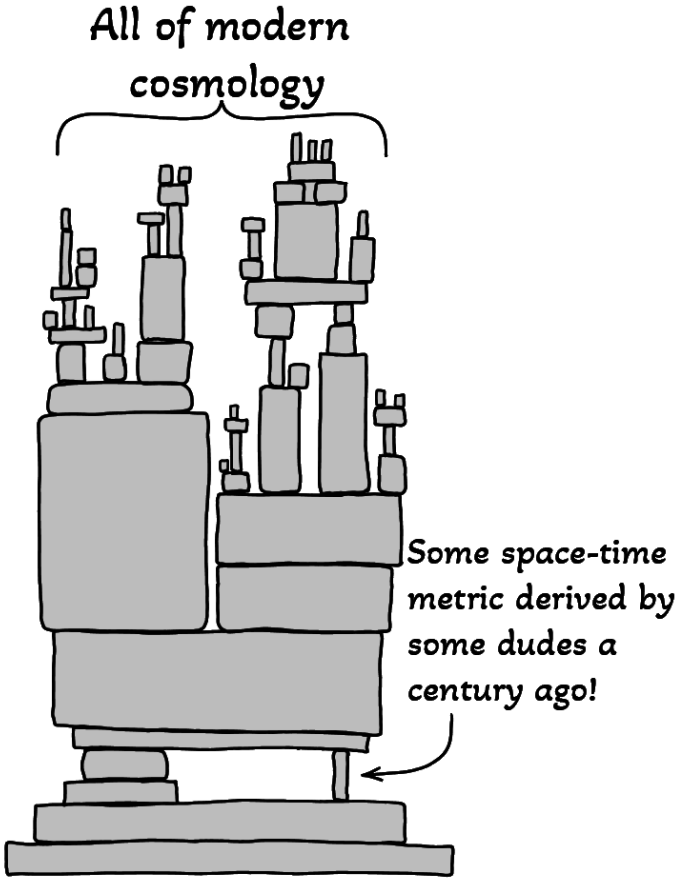


Image credit: Geraint F. Lewis & xkcd

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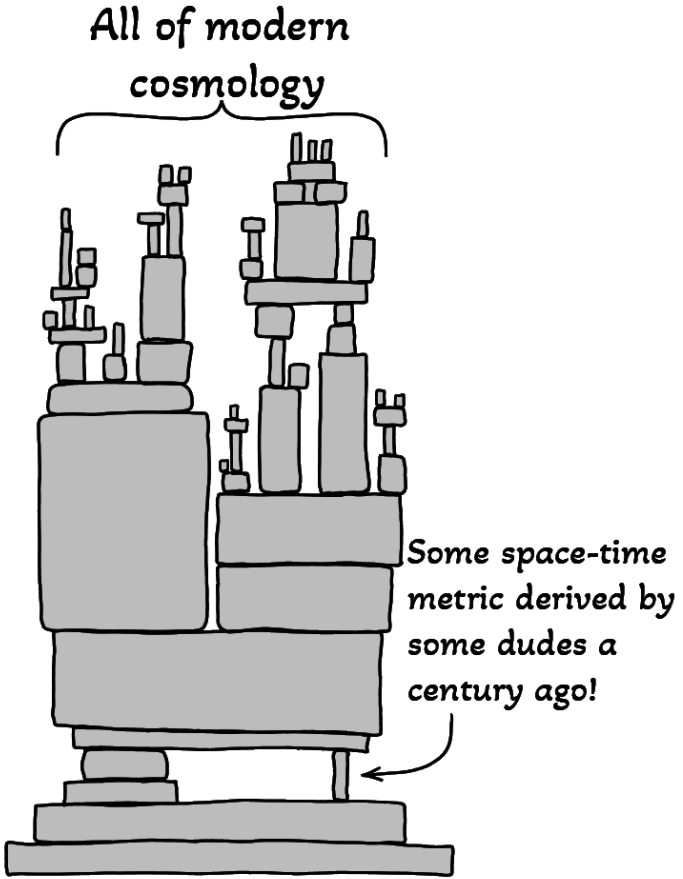

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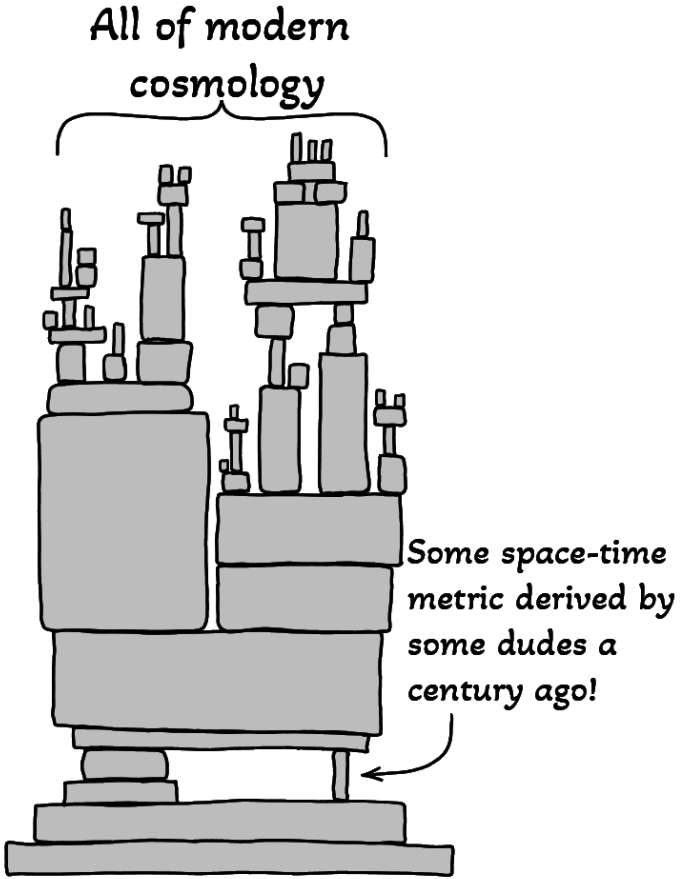

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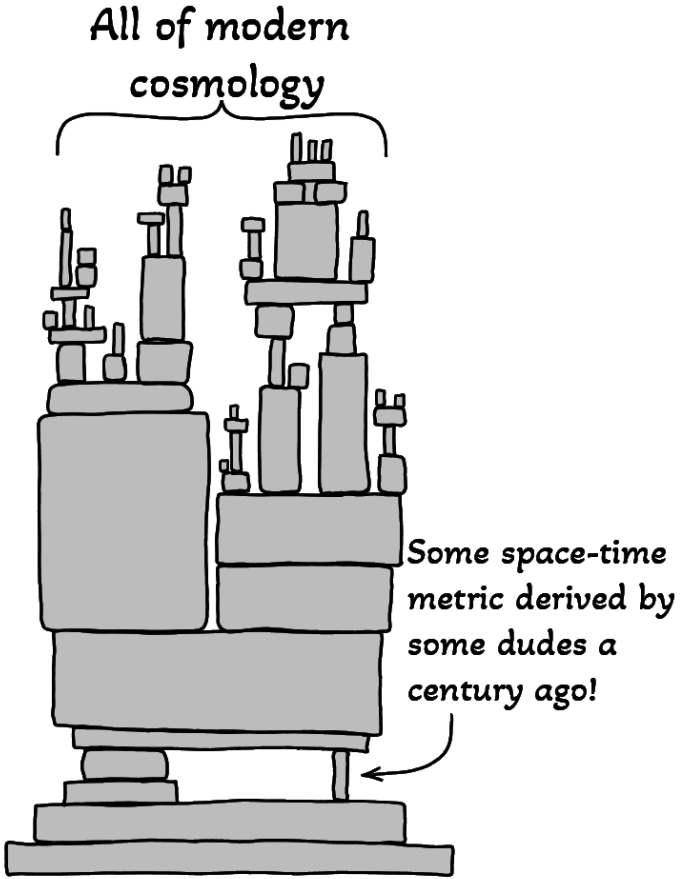

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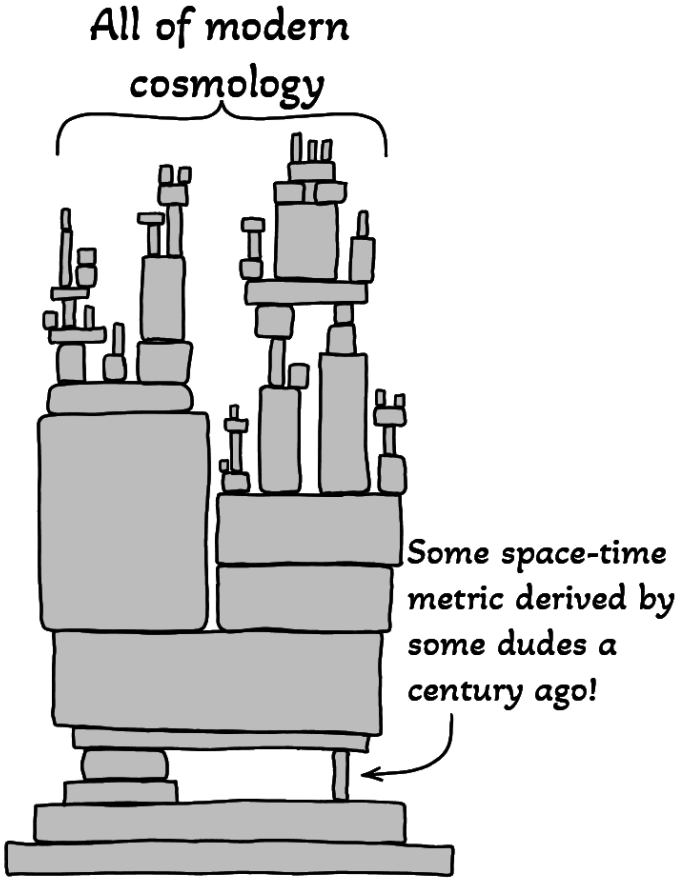

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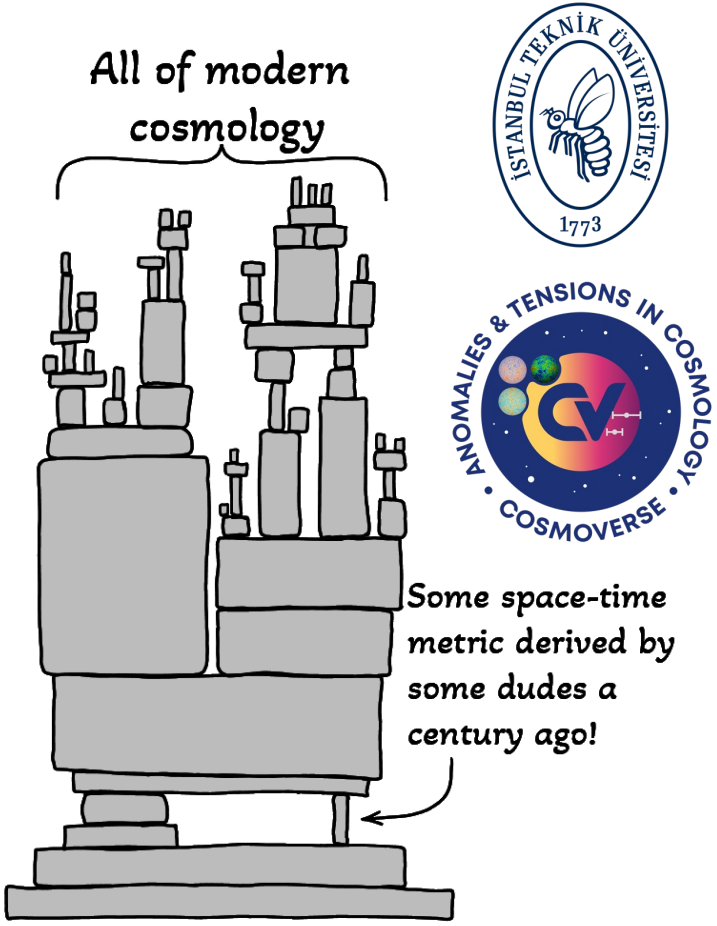
Thank you.
Questions?



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