Copernican Principle Beyond FLRW

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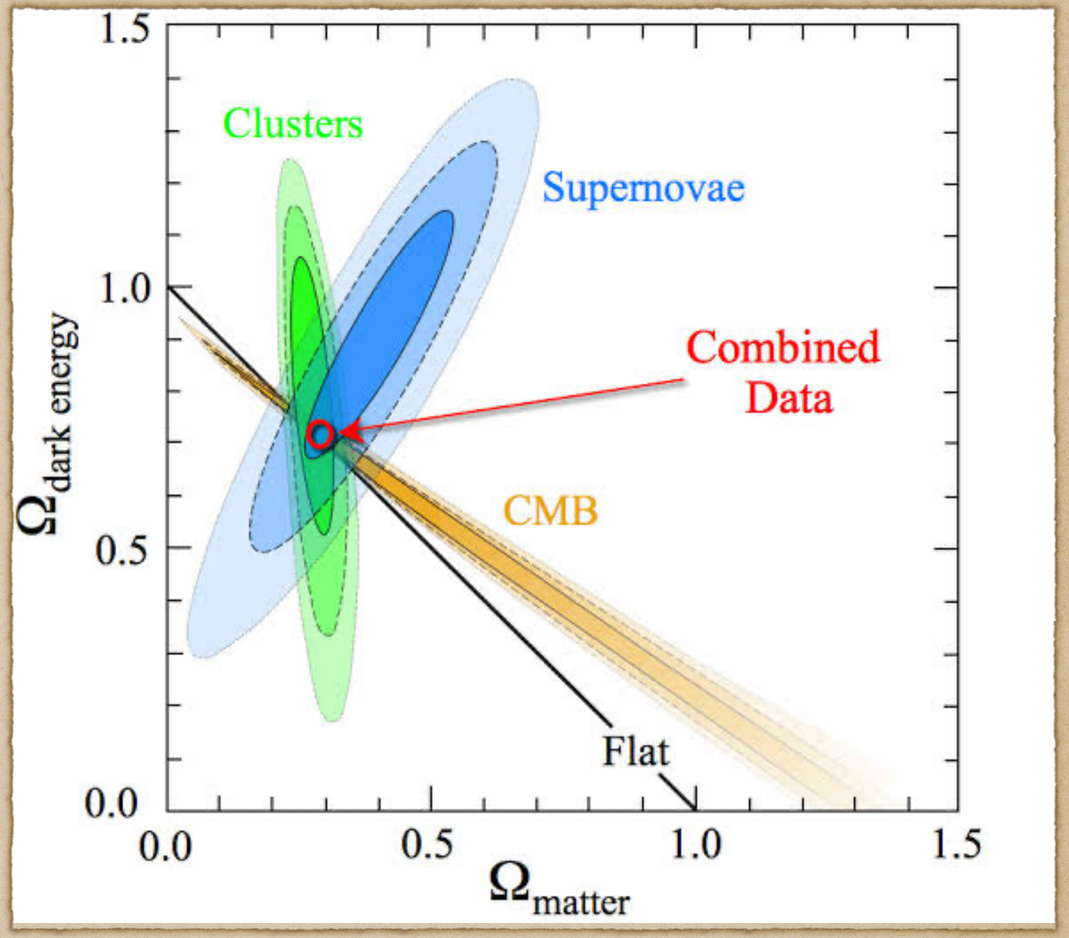
ICPPA2022

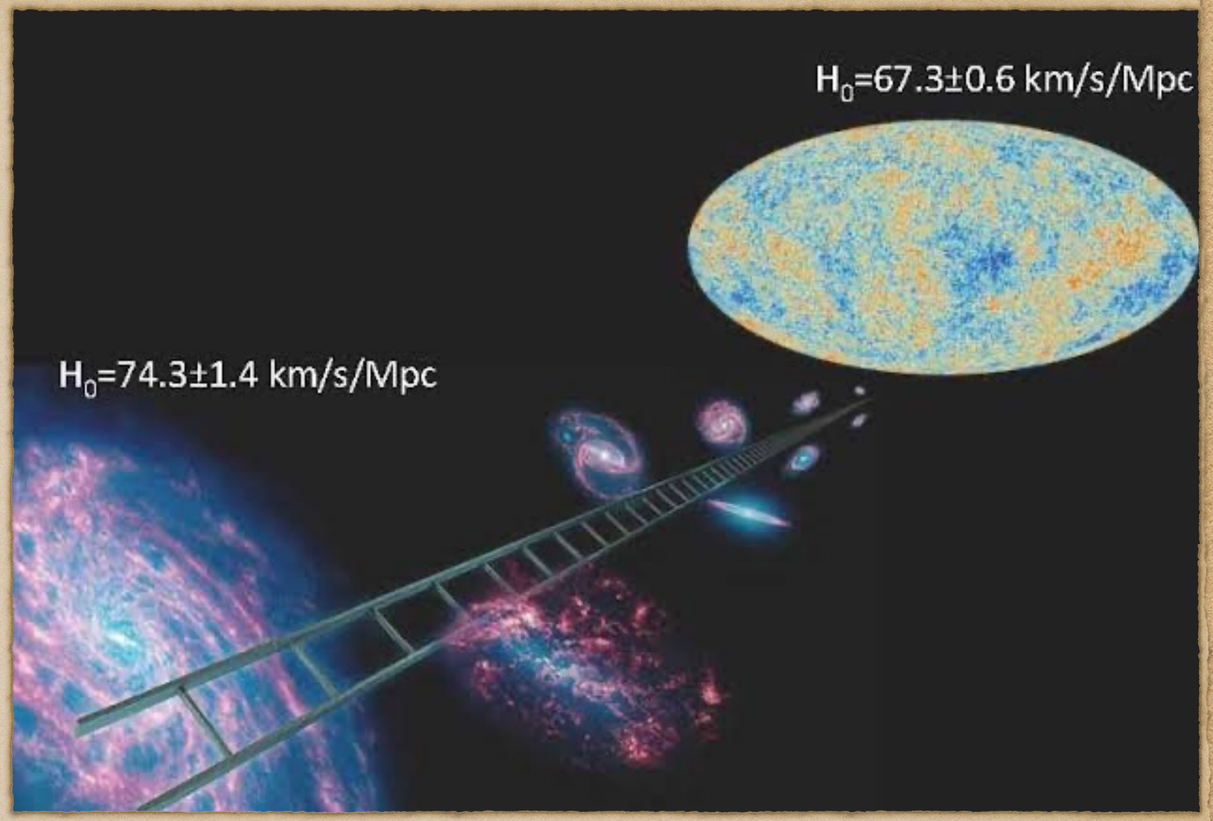
Motivation

Standard Model of Cosmology

ΛCDM model has gloriously succeeded in explaining most of the cosmological observations, Throughout all the redshifts



Cosmological Tensions



For the last couple of decades there is a tension ($\sim 5\sigma$) regarding early and late time cosmologies

Non Kinematic Dipole

There are increasingly numerous hints that have emerged for a non-Kinematic component in the CMB Dipole.

[1] N. J. Secrest, S. von Hausegger, M. Rameez, R. Mohayaee, S. Sarkar and J. Colin, "A Test of the Cosmological Principle with Quasars," Astrophys. J. Lett. **908** (2021) no.2, L51 [arXiv:2009.14826 [astro-ph.CO]];

[2] A. Kashlinsky, F. Atrio-Barandela, D. Kocevski and H. Ebeling, "A measurement of large-scale peculiar velocities of clusters of galaxies: results and cosmological implications," Astrophys. J. Lett. **686** (2009), L49-L52 [arXiv:0809.3734 [astro-ph]].
F. Qin, D. Parkinson, C. Howlett and K. Said, "Cosmic Flow Measurement and Mock Sampling Algorithm of Cosmicflows-4 Tully−Fisher Catalog," Astrophys. J. **922** (2021) no.1, 59 [arXiv:2109.14808 [astro-ph.CO]].

[3] J. Colin, R. Mohayaee, M. Rameez and S. Sarkar, "Evidence for anisotropy of cosmic acceleration," Astron. Astrophys. **631** (2019), L13 [arXiv:1808.04597 [astro-ph.CO]].
R. Mohayaee, M. Rameez and S. Sarkar, "The impact of peculiar velocities on supernova cosmology," [arXiv:2003.10420 [astro-ph.CO]].
A. K. Singal, "Peculiar motion of Solar system from the Hubble diagram of supernovae Ia and its implications for cosmology," [arXiv:2106.11968 [astro-ph.CO]].
N. Horstmann, Y. Pietschke and D. J. Schwarz, "Inference of the cosmic rest-frame from supernovae Ia," [arXiv:2111.03055 [astro-ph.CO]].

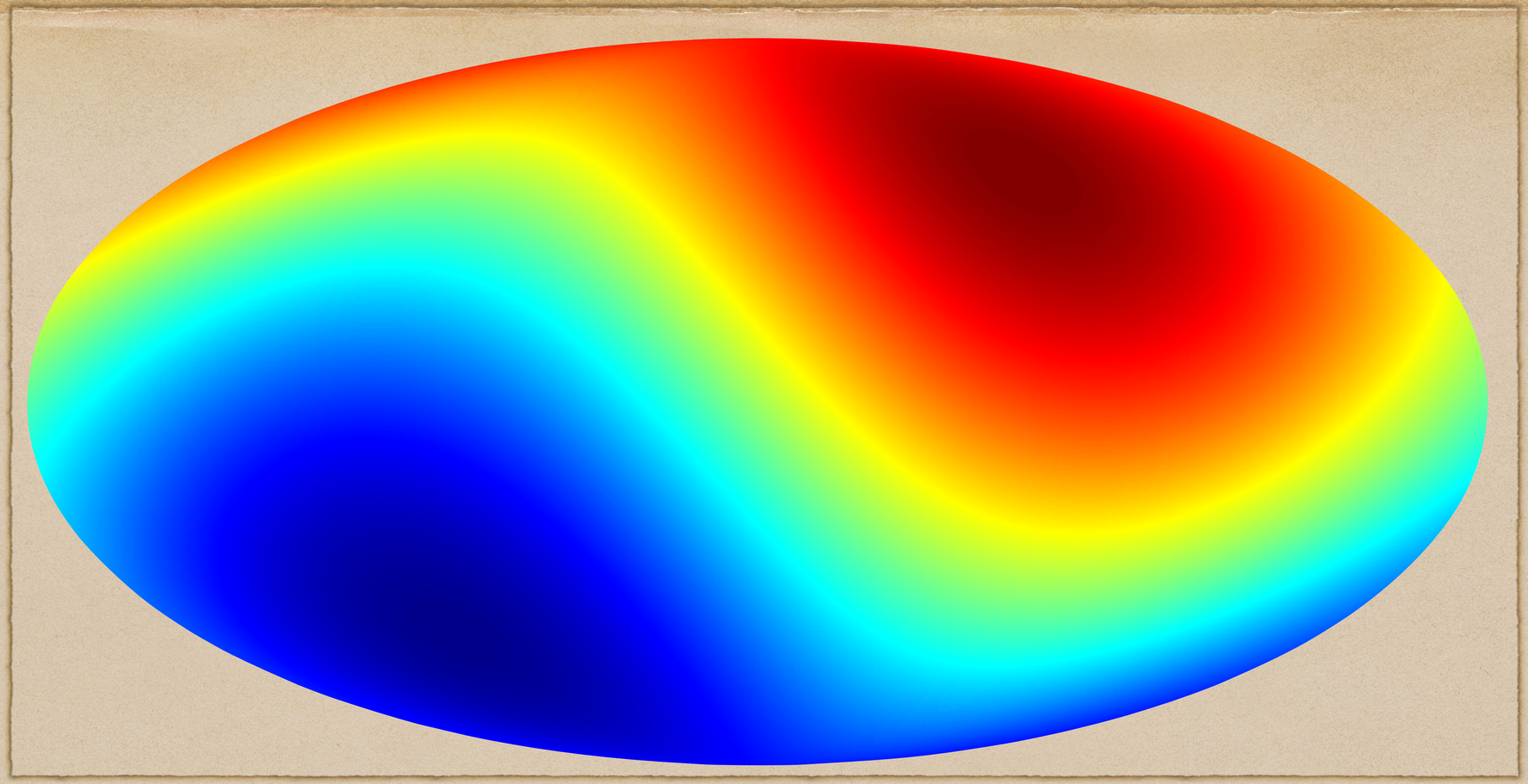
[4] M. Rameez and S. Sarkar, "Is there really a Hubble tension?," Class. Quant. Grav. **38** (2021) no.15, 154005 [arXiv:1911.06456 [astro-ph.CO]].

[5] C. Krishnan, R. Mohayaee, E. Ó. Colgáin, M. M. Sheikh-Jabbari and L. Yin, "Hints of FLRW breakdown from supernovae," Phys. Rev. D **105** (2022) no.6, 063514 [arXiv:2106.02532 [astro-ph.CO]].

[6] V. V. Makarov and N. J. Secrest, "Testing the Cosmological Principle: Astrometric Limits on Systemic Motion of Quasars at Different Cosmological Epochs," Astrophys. J. Lett. **927** (2022) no.1, L4 [arXiv:2202.07536 [astro-ph.GA]];
N. Secrest, S. von Hausegger, M. Rameez, R. Mohayaee and S. Sarkar, "A Challenge to the Standard Cosmological Model," [arXiv:2206.05624 [astro-ph.CO]].
A. K. Singal, "Solar system peculiar motion from the Hubble diagram of quasars and testing the cosmological principle," Mon. Not. Roy. Astron. Soc. **511** (2022) no.2, 1819-1829 [arXiv:2107.09390 [astro-ph.CO]].

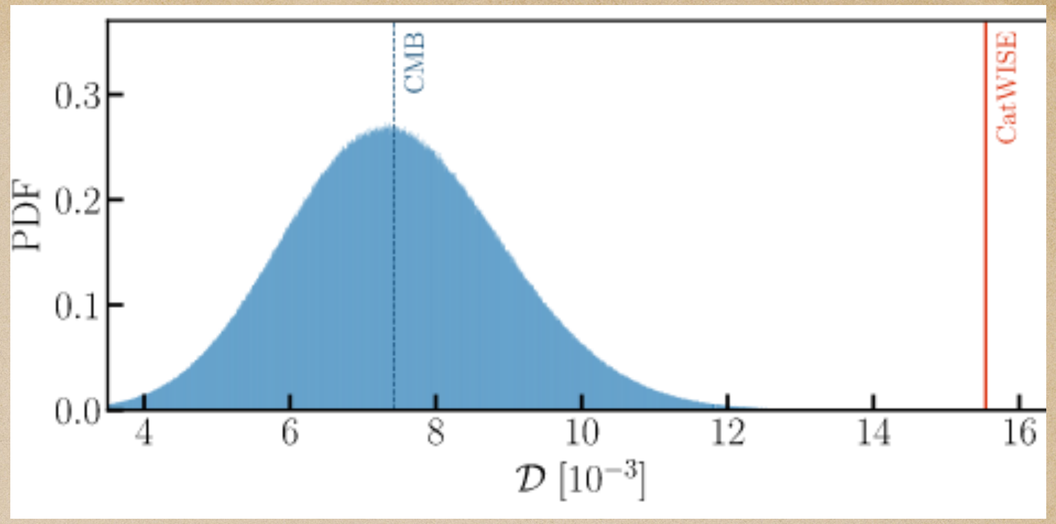
[7] O. Luongo, M. Muccino, E. Ó. Colgáin, M. M. Sheikh-Jabbari and L. Yin, "Larger H0 values in the CMB dipole direction," Phys. Rev. D **105** (2022) no.10, 103510 [arXiv:2108.13228 [astro-ph.CO]];
E. Ó. Colgáin, M. M. Sheikh-Jabbari, R. Solomon, G. Bargiacchi, S. Capozziello, M. G. Dainotti and D. Stojkovic, "Revealing Intrinsic Flat ΛCDM Biases with Standardizable Candles," [arXiv:2203.10558 [astro-ph.CO]].

[8] C. A. P. Bengaly, T. M. Siewert, D. J. Schwarz and R. Maartens, "Testing the standard model of cosmology with the SKA: the cosmic radio dipole," Mon. Not. Roy. Astron. Soc. **486** (2019) no.1, 1350-1357 [arXiv:1810.04960 [astro-ph.CO]].
C. A. P. Bengaly, R. Maartens, N. Randriamiarinarivo and A. Baloyi, "Testing the Cosmological Principle in the radio sky," JCAP **09** (2019), 025 [arXiv:1905.12378 [astro-ph.CO]].

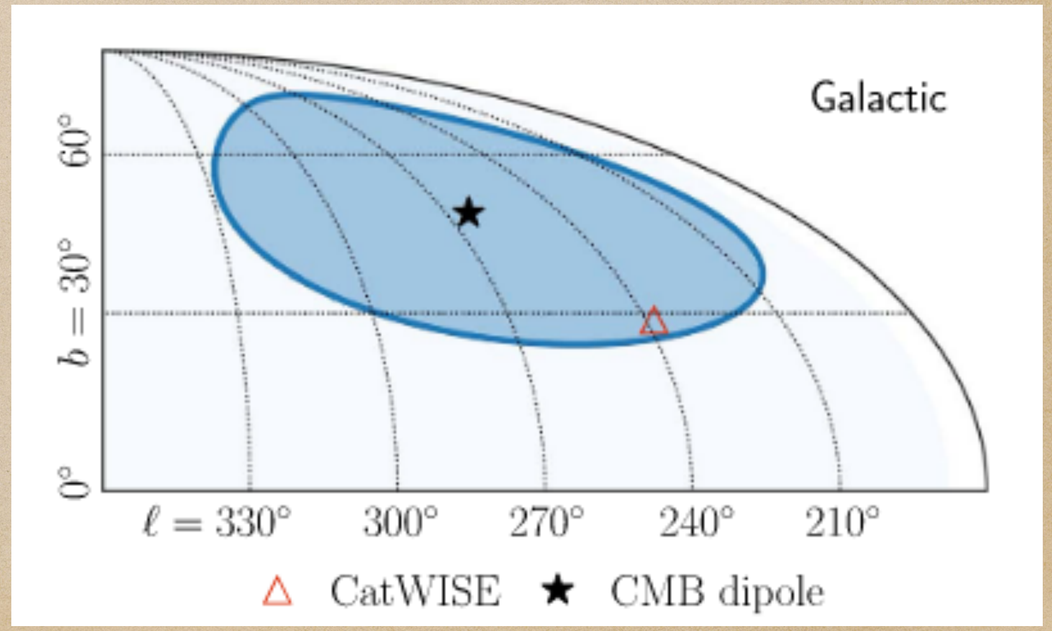


If the Dipole in the CMB is due to "Our motion" w.r.t the "CMB frame" , then we should see similar Dipole in the distribution of the distant sources.

Recent Observation



In one of the recent works by N.J. Secrest, S. von Hausegger, M. Rameez, R. Mohamed, S. Sarkar and J.Colin showed a $\sim 4.9\sigma$ conflict between the expected and measured amplitude of Dipole in the angular distribution of 1.4 million quasar catalogue.



Dipole Cosmological Paradigm

New Directions

Quasars in the CATWISE catalogue are typically at redshifts ~ 1. Thus the most logical question that follows is, "what is the simplest generalization of FLRW paradigm ?"

4 Conclusion

Anisotropies in radio-source number counts can be used to determine a cosmological standard of rest. Current observations determine it to about $\pm 500\ \mathrm{km\ s^{-1}}$, but accurate counts of fainter sources will reduce the error to a level comparable to that set by observations of the microwave background radiation. If the standards of rest determined by the MBR and the number counts were to be in serious disagreement, one would have to abandon either

(a) the idea that the radio sources are at cosmological distances, or

(b) the interpretation of the cosmic microwave radiation as relic radiation from the big bang, or

(c) the standard FRW Universe models.

Thus comparison of these standards of rest provides a powerful consistency test of our understanding of the Universe.

G. F. R. Ellis, J. E. Baldwin, On the expected anisotropy of radio source counts, Monthly Notices of the Royal Astronomical Society, Volume 206, Issue 2, January 1984, Pages 377–381,

Copernican principle In Our Context

Given a prior, what is the most symmetric universe?

No prior $\xrightarrow{c.p}$ Any Maximally symmetric spacetime

Expanding universe $\xrightarrow{c.p}$ Isotropy and Homogenety in the spatial slice (FLRW)

What is our prior?

The universe has a cosmic flow or 'Tilt'

Cosmic flow + Expansion $\xrightarrow{c.p}$ Locally rotationally symmetric Bianchi V

We call this 'Dipole Cosmology'

Cosmological Principle

If one assumes Copernican principle and Observe something (prior). The symmetries inferred are the principles for a cosmological paradigm.

The Standard Cosmological Principle

If the universe appears isotropic from a vantage point on the earth, it infers that the universe is also homogeneous.

These two conditions together are stated as 'The Cosmological Principle'

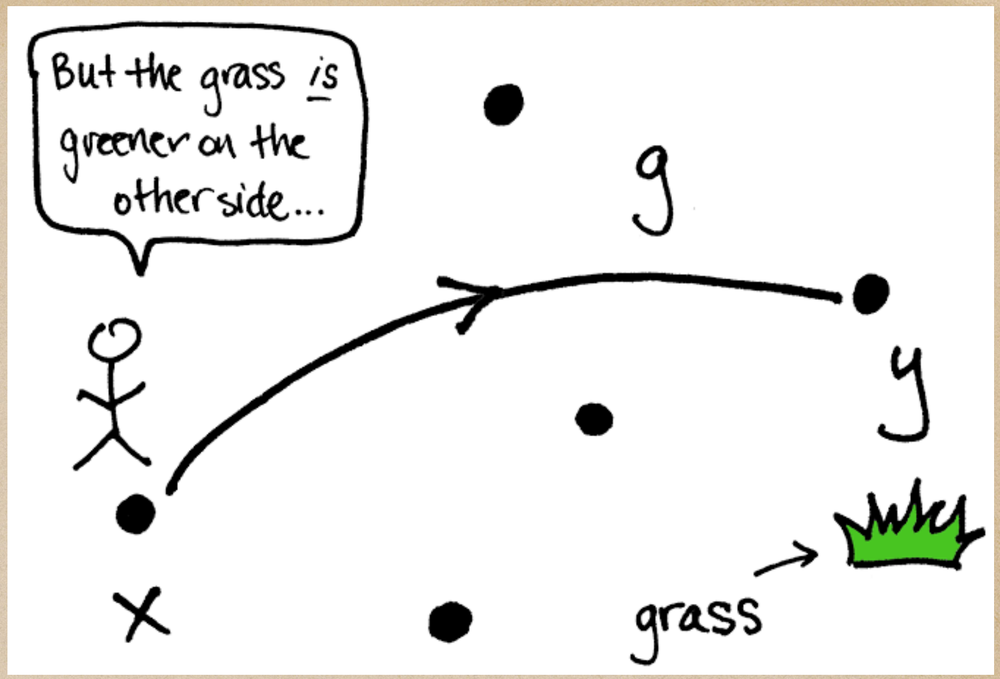
The Dipole Cosmological Principle

1) It is homogeneous in the spatial slices or simply transitive under a group of dimension three.
2) It has a cosmic flow along a spatial direction

The Metric

$$ds^2 = -dt^2 + X^2 dz^2 + Y^2 \exp(-2z)(dx^2 + dy^2)$$

Homogeneity



we can move between any two points in the spatial slice by an action of a group of dimension 3. The three killing vectors for this spacetime are.

$$1)\ \xi_1 = \partial_x$$

$$2)\ \xi_2 = \partial_y$$

$$3)\ \xi_3 = x\partial_x + y\partial_y + \partial_z$$

Stress Energy Tensor

$$T_{ab} = \begin{pmatrix} \rho + (\rho + p)\sinh^2\beta & -(\rho + p)\sinh\beta\cosh\beta & 0 & 0 \\ -(\rho + p)\sinh\beta\cosh\beta & (p + (\rho + p)\sinh^2\beta) & 0 & 0 \\ 0 & 0 & p\exp(-2z)Y^2 & 0 \\ 0 & 0 & 0 & p\exp(-2z)Y^2 \end{pmatrix}$$

Einstein's Equations

	Standard Cosmology (Open)	Dipole Cosmology
First Order	$\left(\frac{\dot{a}}{a}\right)^2 - \frac{k}{a^2} = \frac{\rho}{3}$	$2\frac{\dot{X}}{X}\frac{\dot{Y}}{Y} + \left(\frac{\dot{Y}}{Y}\right)^2 - \frac{3}{X^2} = \rho\cosh^2\beta + p\sinh^2\beta$
		$\frac{2}{X}\left(\frac{\dot{X}}{X} - \frac{\dot{Y}}{Y}\right) = (\rho + p)\sinh\beta\cosh\beta$
Conservation	$\dot{\rho} + 3H(p + \rho) = 0$	$\dot{\rho} + (\rho + p)\left(\frac{\dot{X}}{X} + \frac{2\dot{Y}}{Y} + \tanh\beta\dot{\beta} - \frac{2\tanh\beta}{X}\right) = 0$
		$\dot{p} + (\rho + p)\left(\frac{\dot{X}}{X} + \coth\beta\dot{\beta}\right) = 0$

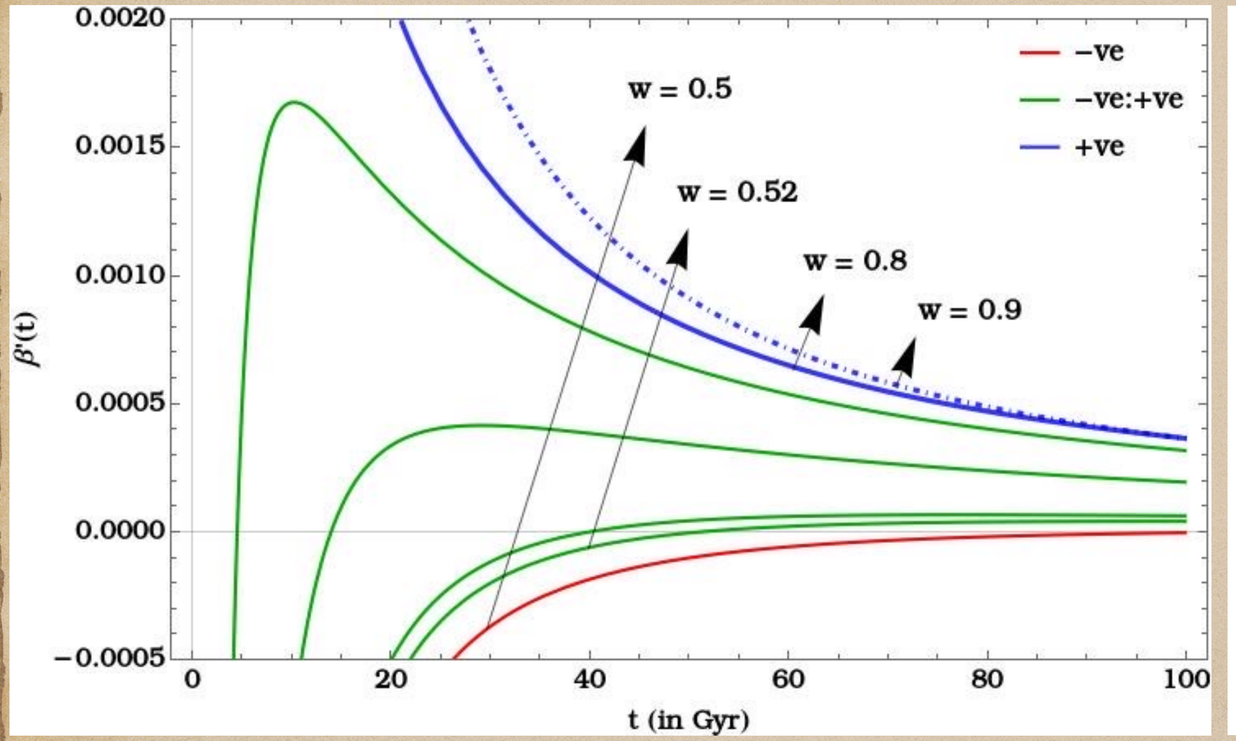
Key Results

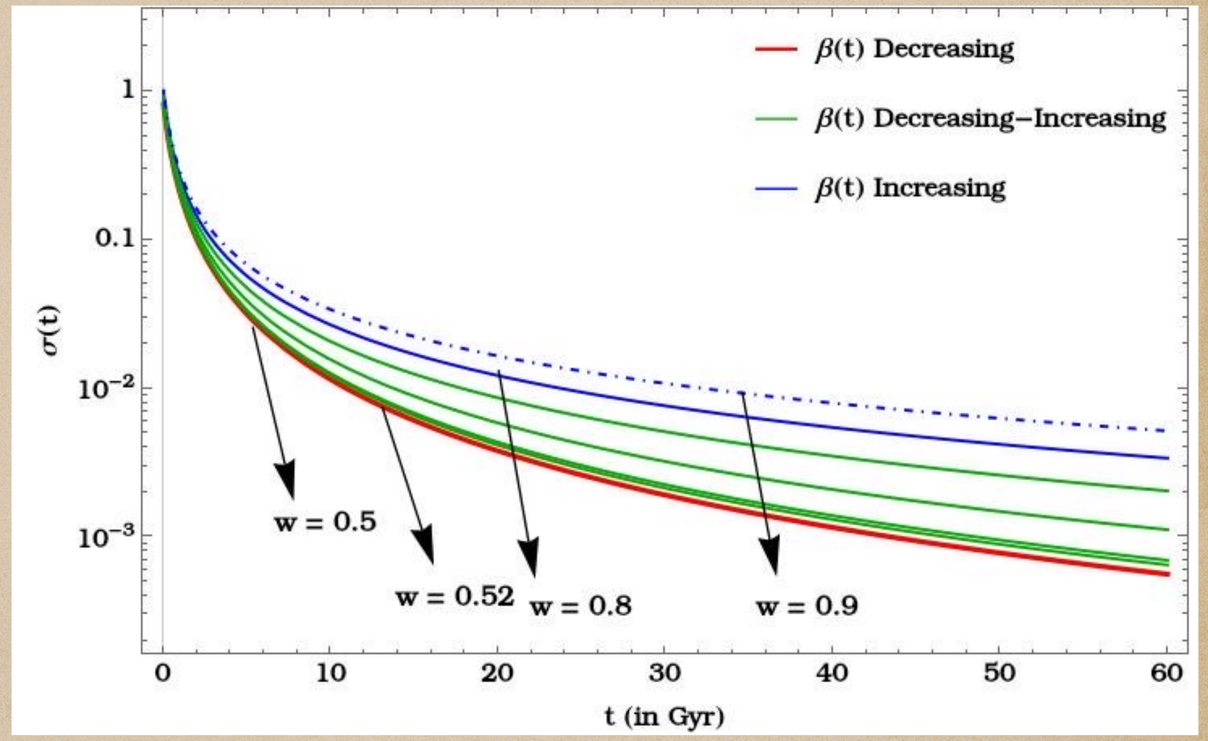
- The consistency is restored by introducing equations of state (EoS), $p = w(t)\rho$

- We will mainly highlight the evolution of the tilt ($\beta(t)$) & shear ($\sigma(t)$). The two main categories of our results are for 1) w(t) = Constant 2) w(t) = a function of time.

- Tilt variation $\dot{\beta}(\coth\beta - w(t)\tanh\beta) = -\frac{\dot{w}}{1+w} + (3w-1)H - \frac{2}{3}\sigma - \frac{2w\tanh\beta}{X}$

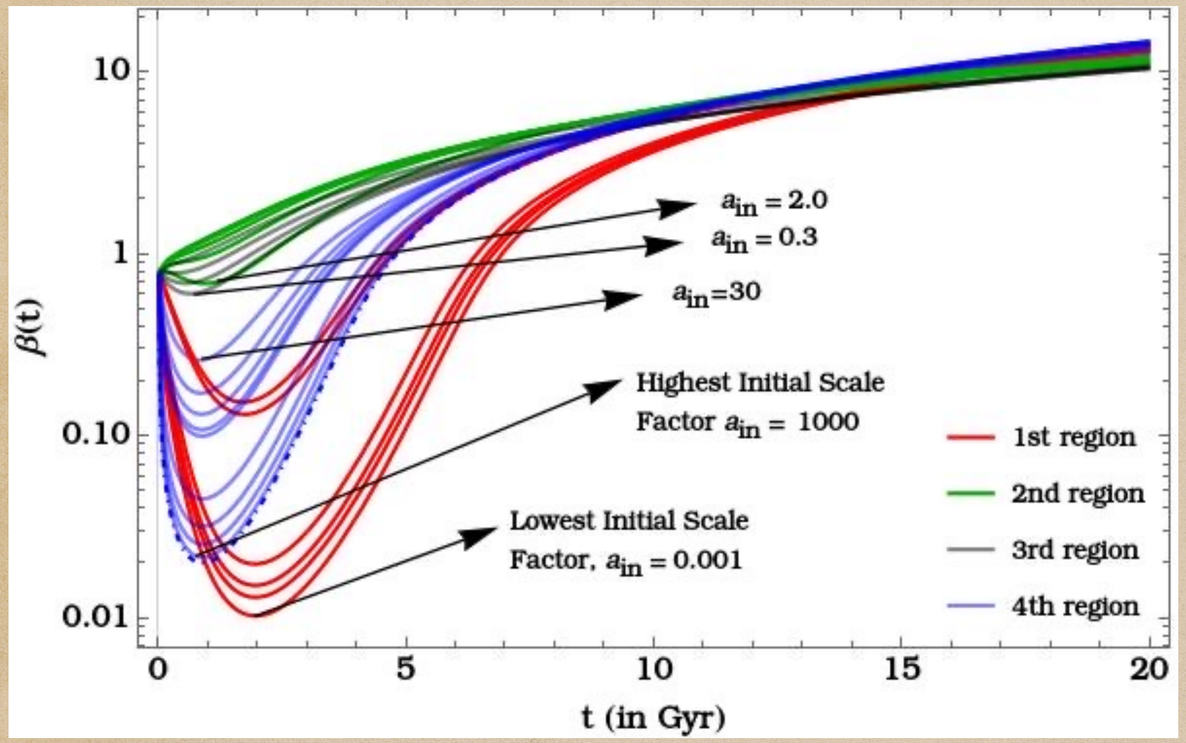
- Main message: We can have increasing tilt for an universe with late time acceleration.

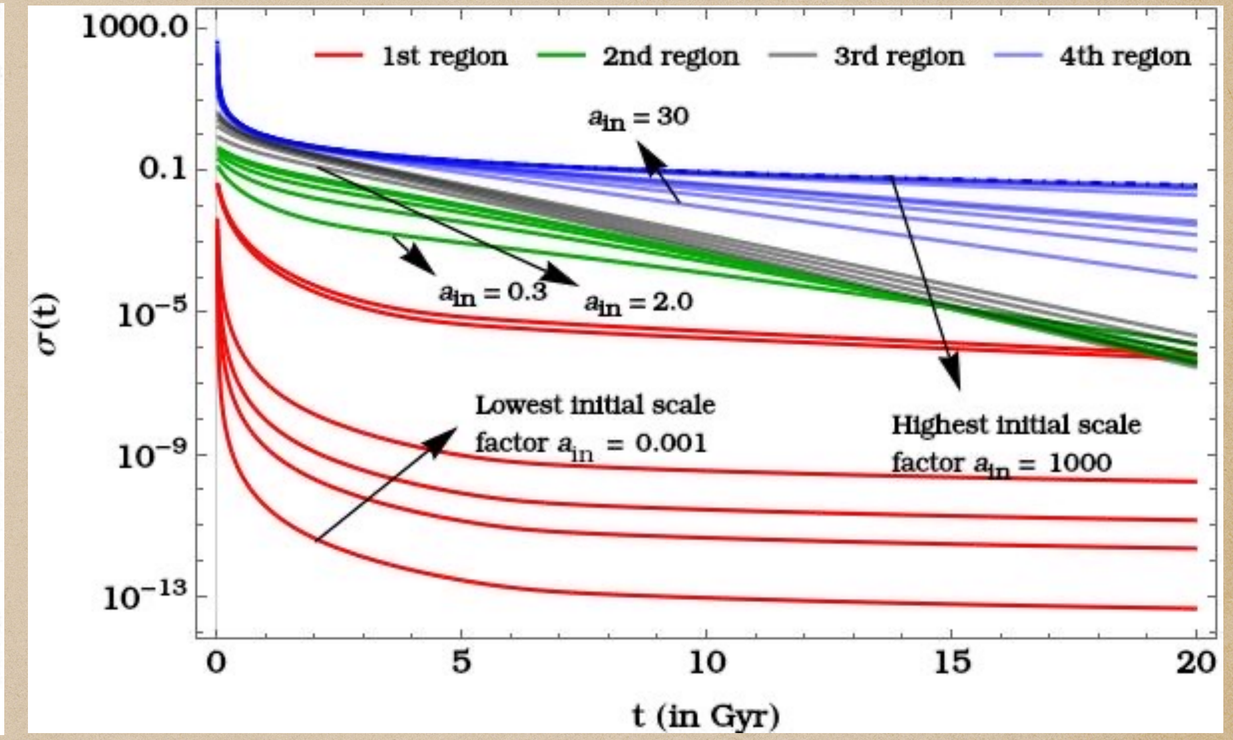




Plots for $\dot{\beta}$ and shear for w = constant > 1/3 cases. See also work by A. Coley (arxiv: gr-qc/0605128v1)

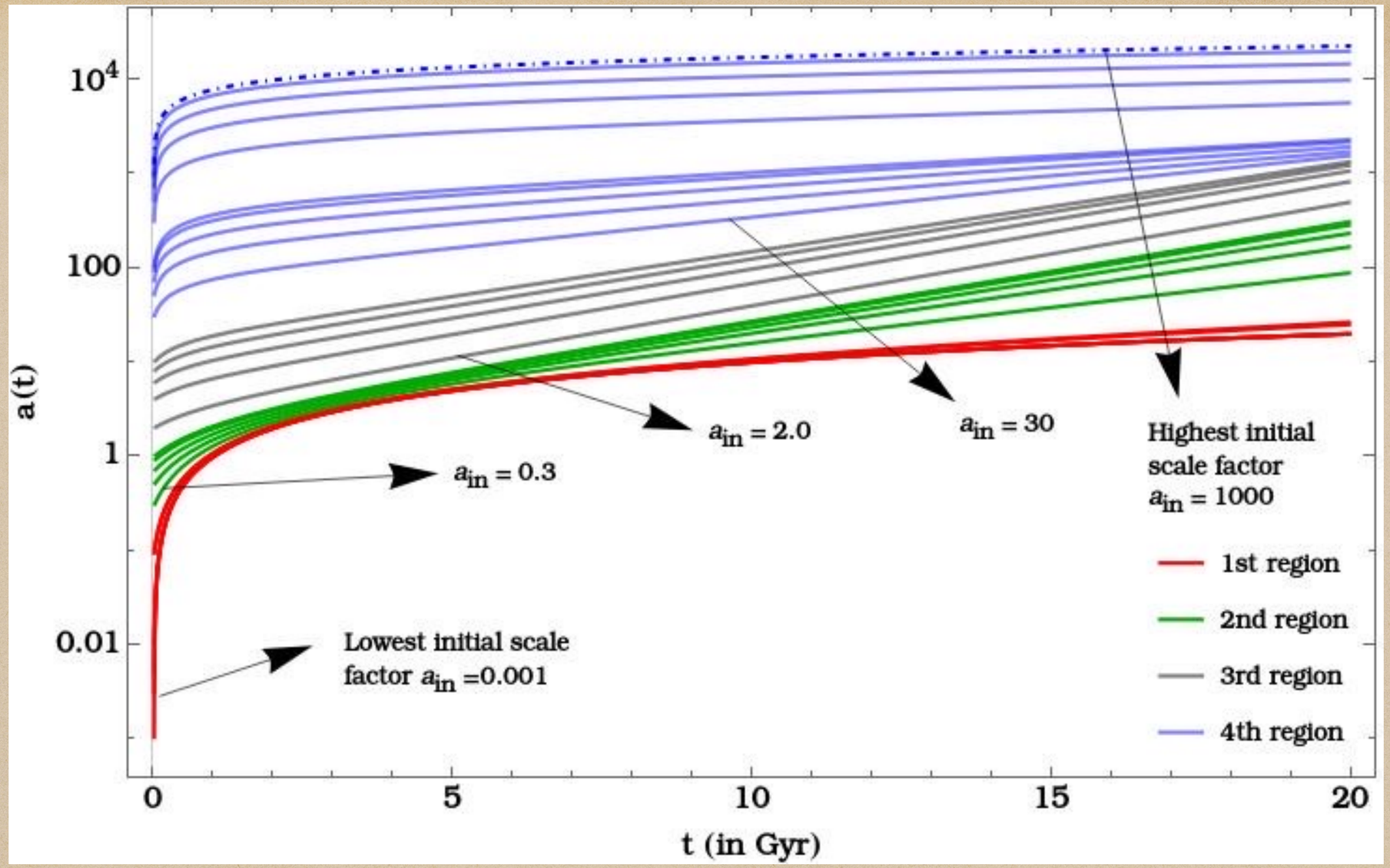
arXiv: 2209.14918[astro-ph.CO]





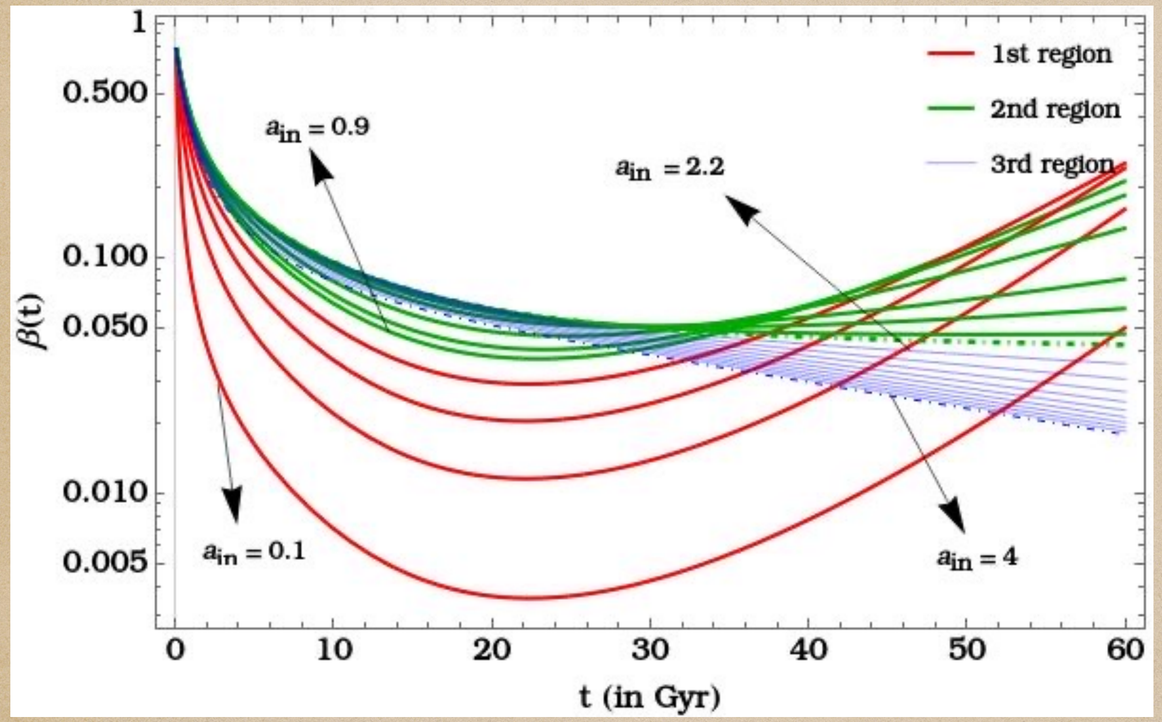
Plots for the 'Tilt' and 'Shear' for an effective EoS $w(t) = -1 + a\exp(-bt)$

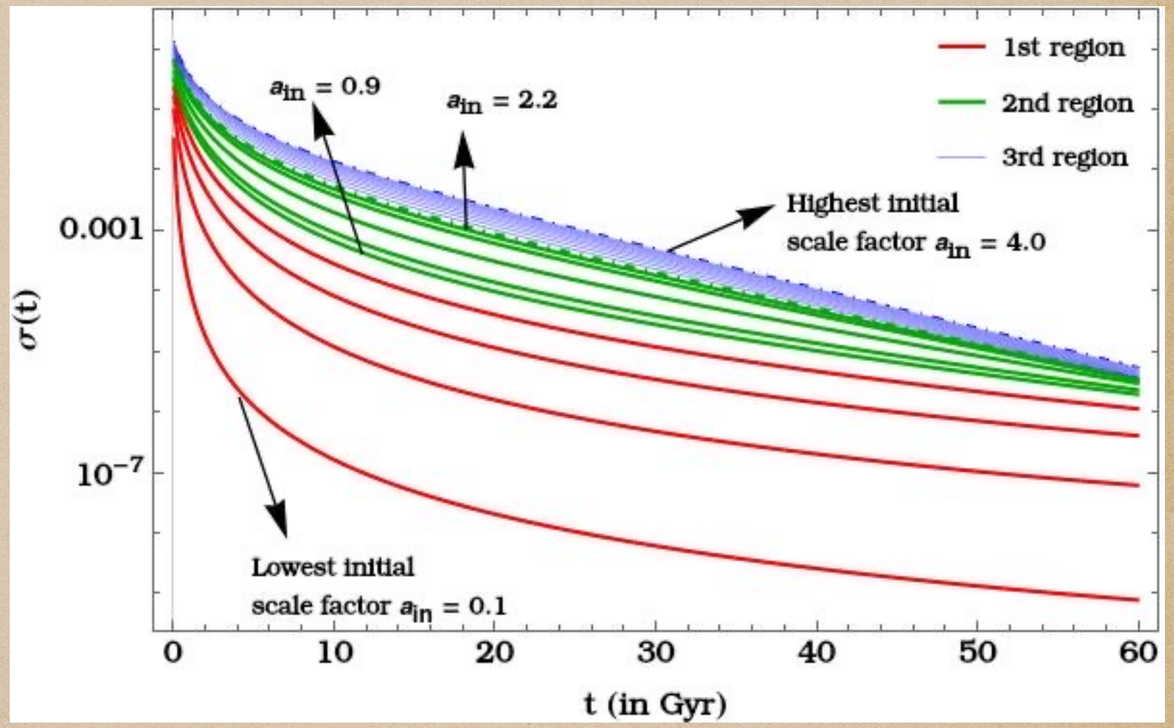
arXiv: 2209.14918[astro-ph.CO]



Evolution of 'Scale factor' for effective EoS $w(t) = -1 + \exp(-bt)$.

arXiv: 2209.14918[astro-ph.CO]





Evolution of 'Tilt' & 'Shear' for $w(t) = w_{LCDM} = -\tanh^2\left(1.5\sqrt{\Omega_\Lambda H_0^2}\,t\right)$

arXiv: 2209.14918 [astro-ph.CO]

Summary & Conclusions

- We look for an Copernican ansatz that allows a cosmic flow.
- The spacetime turns out to have Spatially Homogeneous slice, with an axial symmetry along a spatial direction.
- Owing to the SH, the field equations are ODEs & the solutions are easily tractable.
- As tilt is a function of time, we are expected to find different angular distributions for observations at different redshifts.
- This system has a instability in tilt. It argues for a tilt growth at late times even for a minimal initial tilt perturbation (nearly isotropic CMB).

Thank you