Inhomogeneity beyond the perturbation theory in cosmology, i.e. beyond the cosmological principle

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The cosmological principle is assumed to apply in scales larger than superclusters

~ 100 Mpc or

~ 300 Mly or

$\sim 3 \times 10^{21}$ km

The cosmological principle

=> FLRW metric

So discarding the cosmological principle

=> metric more complex than the FLRW metric

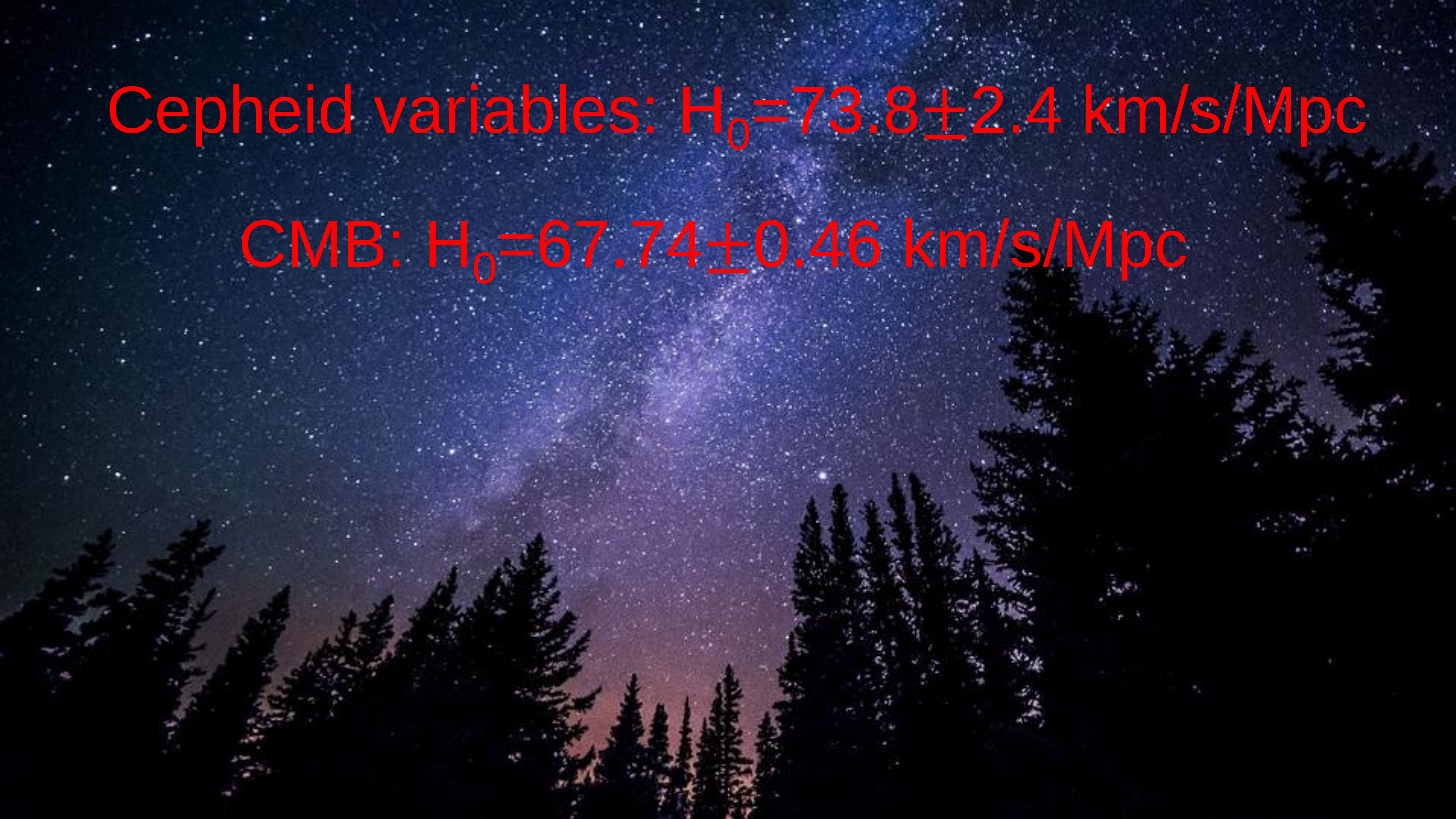
=> more complex equations

Why on Earth would we do this?

The accuracy of the observations continuously increases – we should test our assumptions rather than trust them blindly

Cepheid variables: H_0=73.8$\pm$2.4 km/s/Mpc

CMB: H_0=67.74$\pm$0.46 km/s/Mpc



Cepheid variables: H_0=73.8±2.4 km/s/Mpc

CMB: H_0=67.74±0.46 km/s/Mpc

Answer: a huge void (larger than superclusters)

COMPOSITE sample: Local Group moves at ~350 km/s w.r.t. CMB frame

CMB: Local Group moves at ~620 km/s w.r.t. CMB frame

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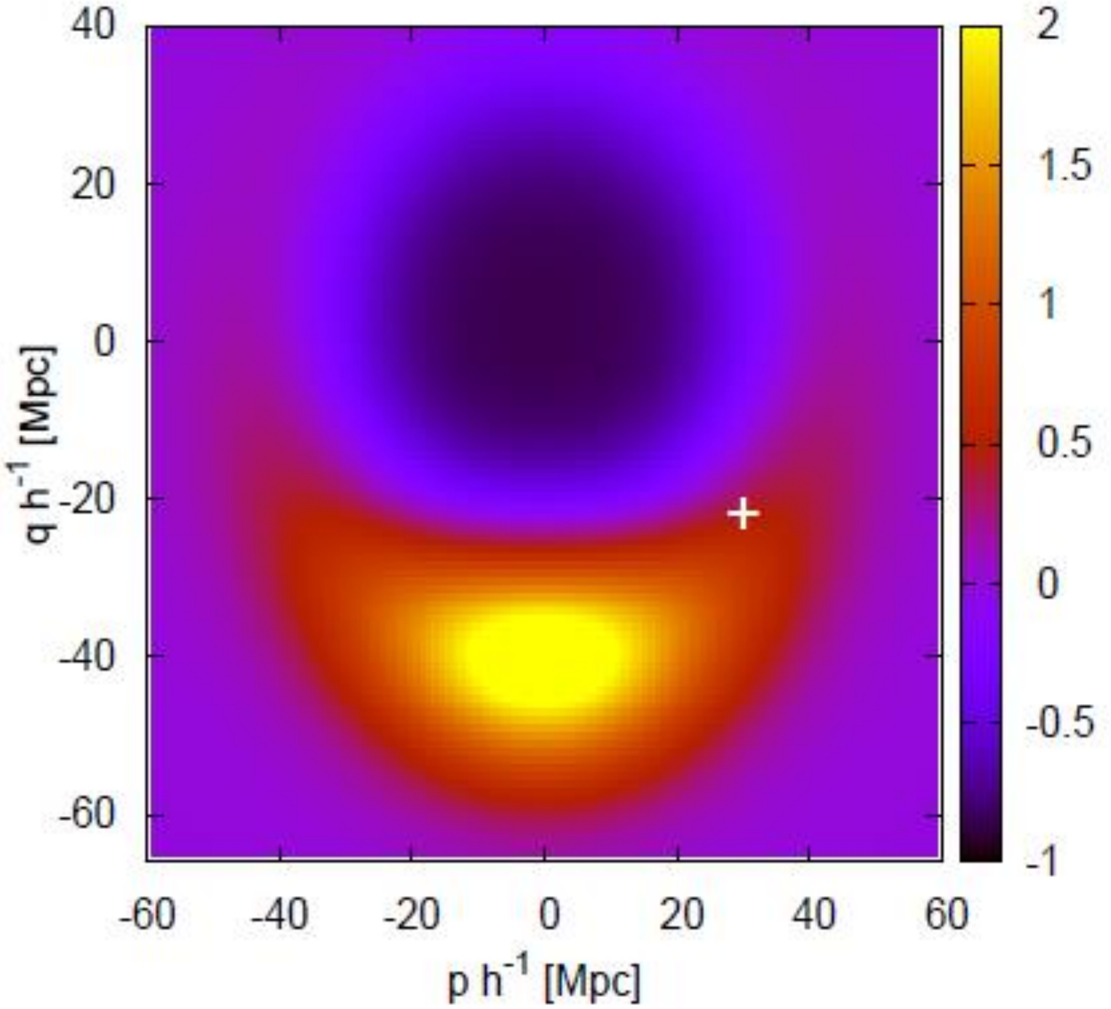
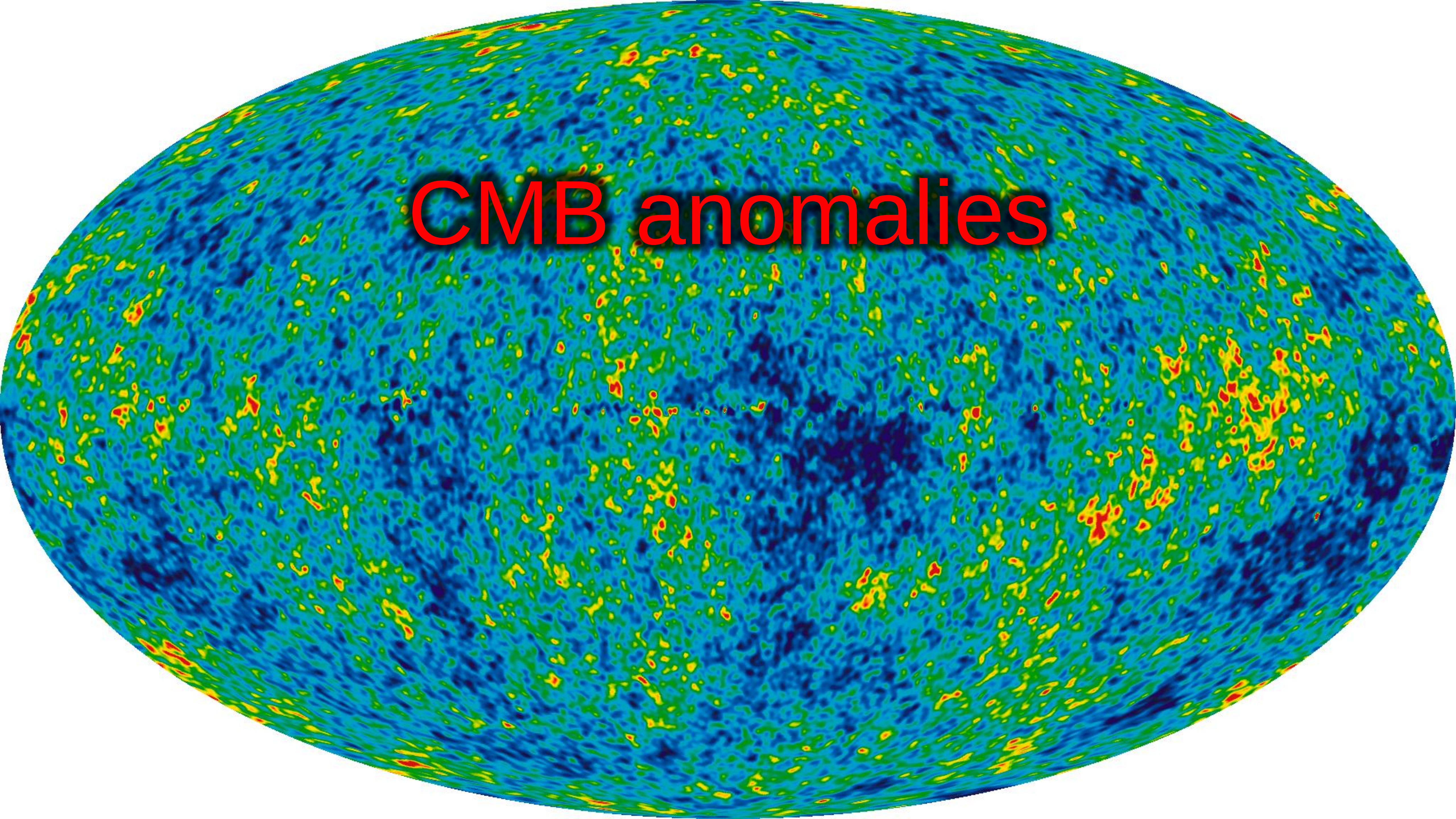
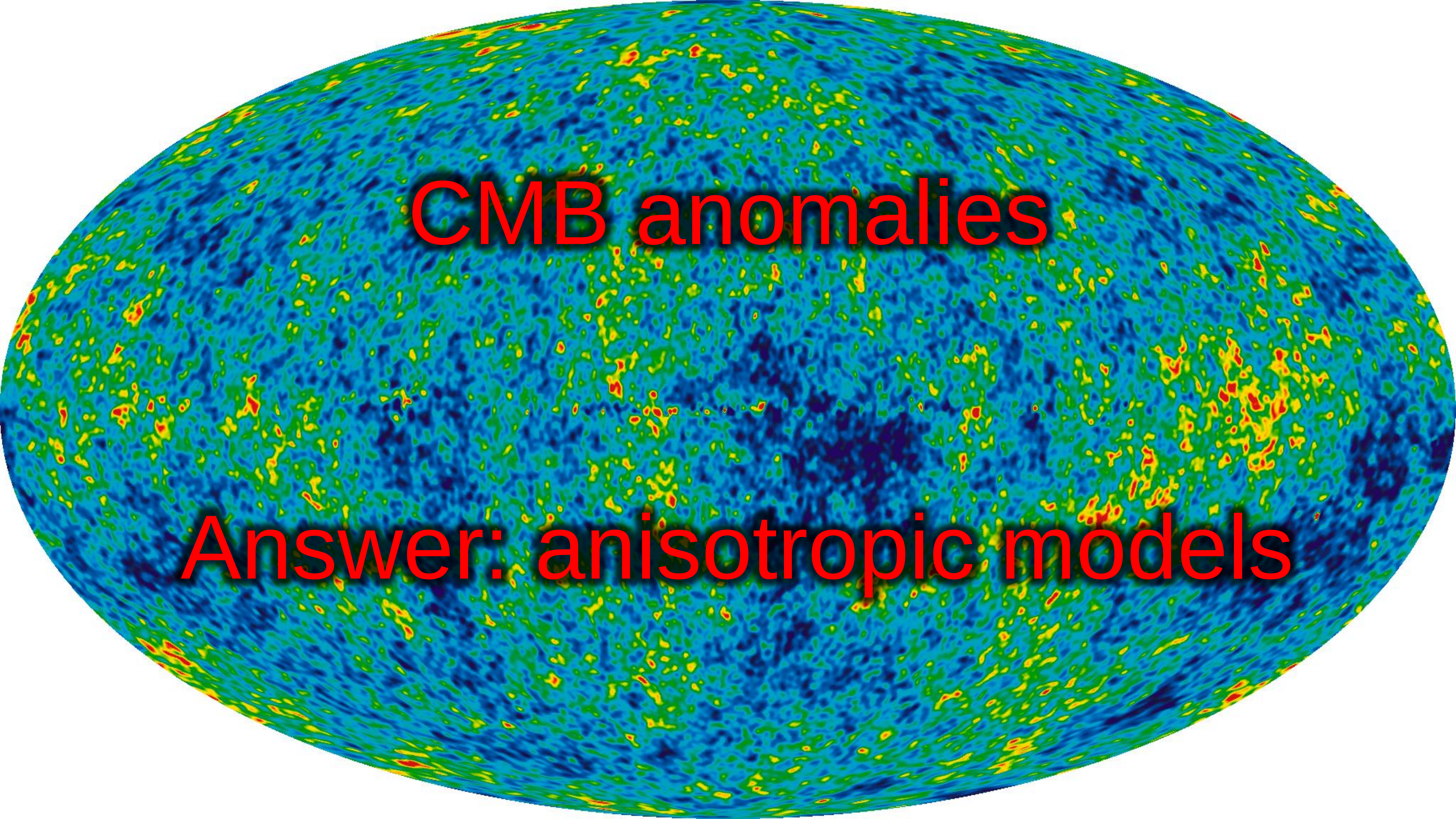
Answer: Local Void and Great Attractor



K. Bolejko, M. A. Nazer, D. L. Wiltshire,
JCAP06(2016)035


CMB anomalies


CMB anomalies
Answer: anisotropic models

Tilted perfect fluid Bianchi VII_h can explain some of the anomalies…

Tilted perfect fluid Bianchi VII_h can explain some of the anomalies…

…but only if it is inconsistent with other cosmological observations.

T. R. Jaffe, S. Hervik, A. J. Banday, and K. M. Górski, Astrophys.J.644:701-708,2006

What if…

non-

Tilted perfect fluid Bianchi VII_h can explain some of the anomalies…

P. Sundell and T. Koivisto,
PRD 92, 123529 (2015)

Bianchi VII$_h$

$$
\begin{aligned}
\Sigma_+' &= (q-2)\Sigma_+ + 3(\Sigma_{12}^2+\Sigma_{13}^2) - 2N^2 + \frac{\gamma\Omega}{2G_+}\left(-2v_1^2+v_2^2+v_3^2\right)\\
\Sigma_-' &= (q-2-2\sqrt{3}\Sigma_{23}\lambda)\Sigma_- + \sqrt{3}(\Sigma_{12}^2-\Sigma_{13}^2) + 2AN + \frac{\sqrt{3}\gamma\Omega}{2G_+}\left(v_2^2-v_3^2\right)\\
\Sigma_{12}' &= \left(q-2-3\Sigma_+-\sqrt{3}\Sigma_-\right)\Sigma_{12} - \sqrt{3}\left(\Sigma_{23}+\Sigma_-\lambda\right)\Sigma_{13} + \frac{\sqrt{3}\gamma\Omega}{G_+}v_1v_2\\
\Sigma_{13}' &= \left(q-2-3\Sigma_++\sqrt{3}\Sigma_-\right)\Sigma_{13} - \sqrt{3}\left(\Sigma_{23}-\Sigma_-\lambda\right)\Sigma_{12} + \frac{\sqrt{3}\gamma\Omega}{G_+}v_1v_3\\
\Sigma_{23}' &= (q-2)\Sigma_{23} - 2\sqrt{3}N^2\lambda + 2\sqrt{3}\lambda\Sigma_-^2 + 2\sqrt{3}\Sigma_{12}\Sigma_{13} + \frac{\sqrt{3}\gamma\Omega}{G_+}v_2v_3\\
N' &= \left(q+2\Sigma_++2\sqrt{3}\Sigma_{23}\lambda\right)N\\
\lambda' &= 2\sqrt{3}\Sigma_{23}\left(1-\lambda^2\right)\\
A' &= (q+2\Sigma_+)A.
\end{aligned}
$$

$$
\begin{aligned}
q &= 2\Sigma^2 + \frac{1}{2}\frac{(3\gamma-2)+(2-\gamma)V^2}{1+(\gamma-1)V^2}\Omega\\
\Sigma^2 &= \Sigma_+^2+\Sigma_-^2+\Sigma_{12}^2+\Sigma_{13}^2+\Sigma_{23}^2\\
\mathcal{S} &= \Sigma_{ab}c^ac^b, \quad c^ac_a=1, \quad v^a = Vc^a,\\
V^2 &= v_1^2+v_2^2+v_3^2,\\
T &= \frac{\left[(3\gamma-4)-2(\gamma-1)Av_1\right](1-V^2)+(2-\gamma)V^2\mathcal{S}}{1-(\gamma-1)V^2}\\
G_+ &= 1+(\gamma-1)V^2.
\end{aligned}
$$

$$
\begin{aligned}
\Omega' &= \frac{\Omega}{G_+}\left\{2q-(3\gamma-2)+2\gamma Av_1+\left[2q(\gamma-1)-(2-\gamma)-\gamma\mathcal{S}\right]V^2\right\}\\
v_1' &= (T+2\Sigma_+)v_1 - 2\sqrt{3}\Sigma_{13}v_3 - 2\sqrt{3}\Sigma_{12}v_2 - A\left(v_2^2+v_3^2\right) - \sqrt{3}N\left(v_2^2-v_3^2\right)\\
v_2' &= \left(T-\Sigma_+-\sqrt{3}\Sigma_-\right)v_2 - \sqrt{3}\left(\Sigma_{23}+\Sigma_-\lambda\right)v_3 + \sqrt{3}\lambda Nv_1v_3 + \left(A+\sqrt{3}N\right)v_1v_2\\
v_3' &= \left(T-\Sigma_++\sqrt{3}\Sigma_-\right)v_3 - \sqrt{3}\left(\Sigma_{23}-\Sigma_-\lambda\right)v_2 - \sqrt{3}\lambda Nv_1v_2 + \left(A-\sqrt{3}N\right)v_1v_3\\
V' &= \frac{V(1-V^2)}{1-(\gamma-1)V^2}\left[(3\gamma-4)-2(\gamma-1)Av_1-\mathcal{S}\right],
\end{aligned}
$$

$$
\begin{aligned}
1 &= \Sigma^2+A^2+N^2+\Omega\\
0 &= 2\Sigma_+A+2\Sigma_-N+\frac{\gamma\Omega v_1}{G_+}\\
0 &= -\left[\Sigma_{12}(N+\sqrt{3}A)+\Sigma_{13}\lambda N\right]+\frac{\gamma\Omega v_2}{G_+}\\
0 &= \left[\Sigma_{13}(N-\sqrt{3}A)+\Sigma_{12}\lambda N\right]+\frac{\gamma\Omega v_3}{G_+}\\
0 &= A^2+3h\left(1-\lambda^2\right)N^2.
\end{aligned}
$$

Summary

The impact of inhomogeneities beyond the perturbation theory in cosmology are poorly understood

Imparticularly now, the era of precision cosmology offers an opportunity to truly probe this.

Thank you!