Introduction to Cosmology and Structure Formation

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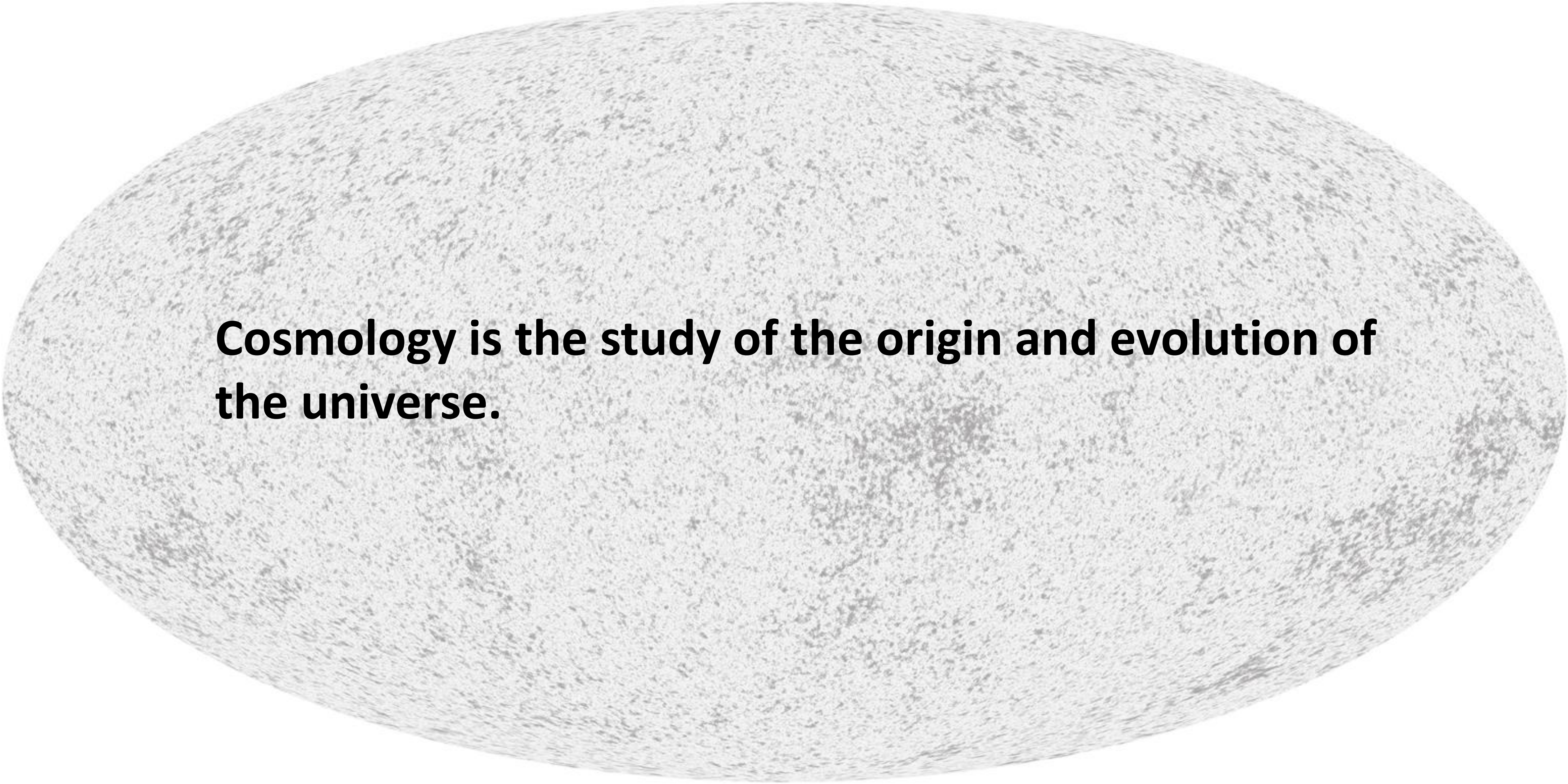
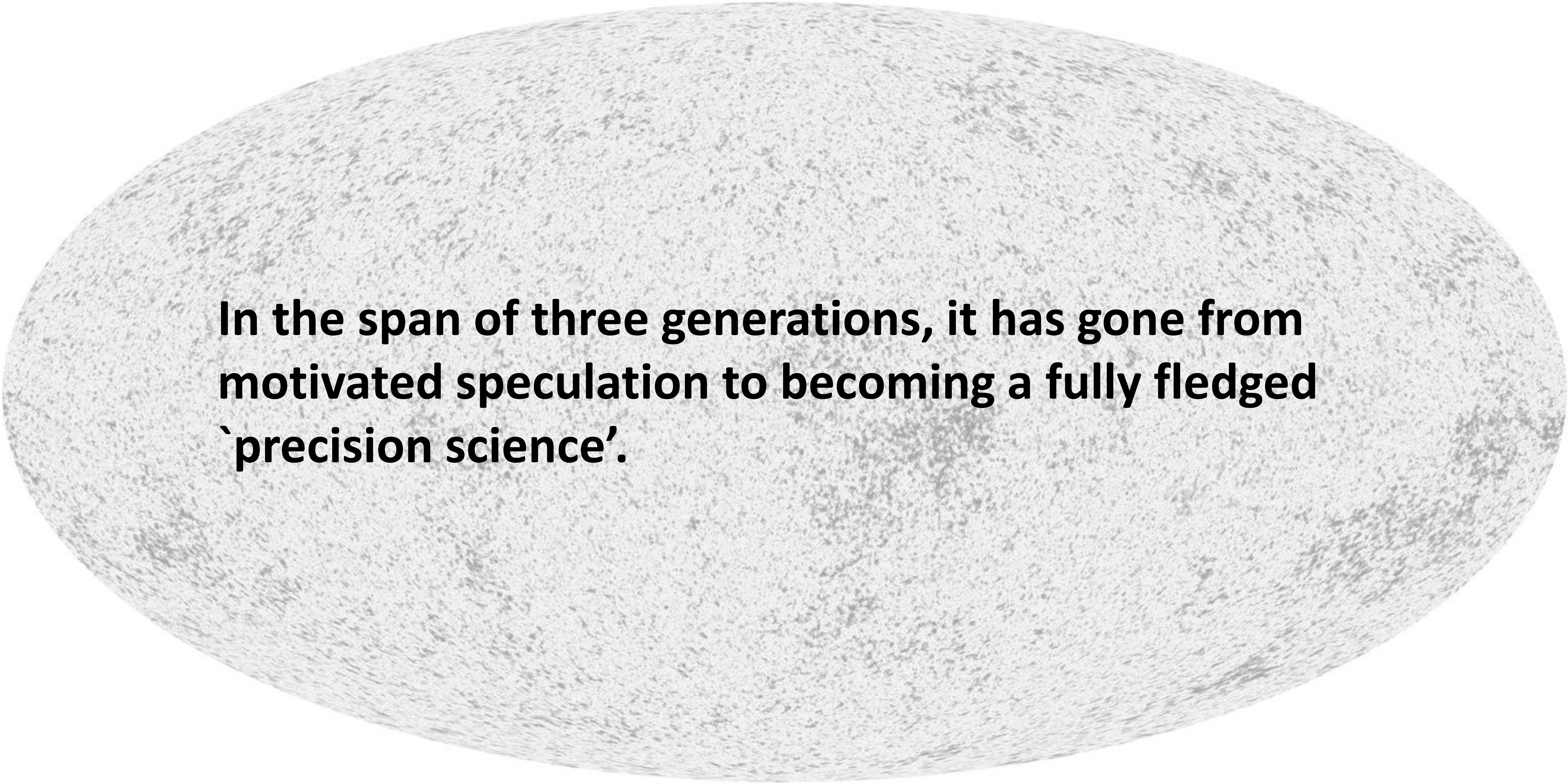
NBIA winter school
Jan 3 2019

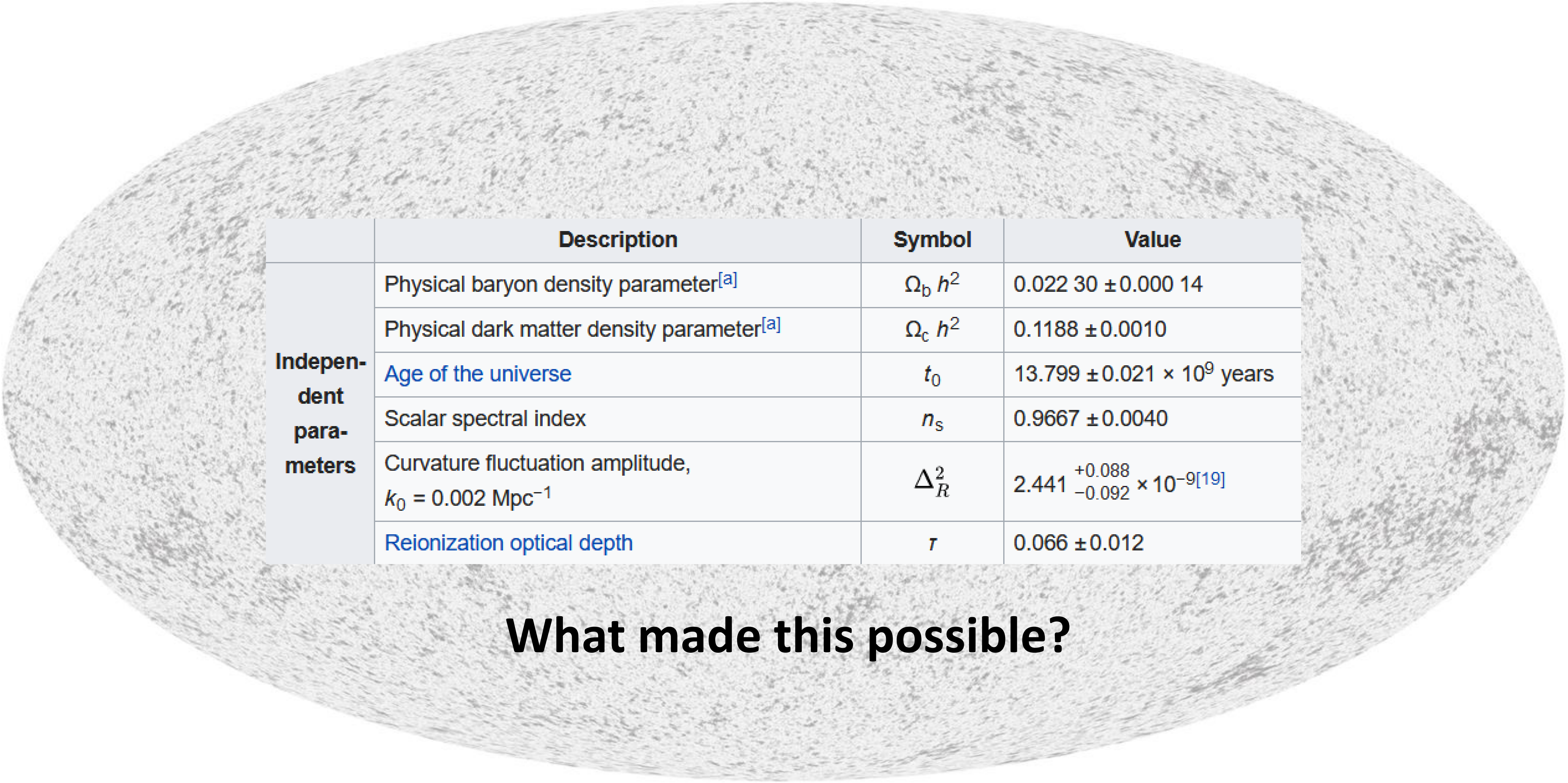


Cosmology is the study of the origin and evolution of the universe.



In the span of three generations, it has gone from motivated speculation to becoming a fully fledged \`precision science'.

	Description	Symbol	Value
Independent parameters	Physical baryon density parameter[a]	$\Omega_b h^2$	0.022 30 ± 0.000 14
	Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ± 0.0010
	Age of the universe	t_0	13.799 ± 0.021 × 10^9 years
	Scalar spectral index	n_s	0.9667 ± 0.0040
	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$[19]
	Reionization optical depth	τ	0.066 ± 0.012



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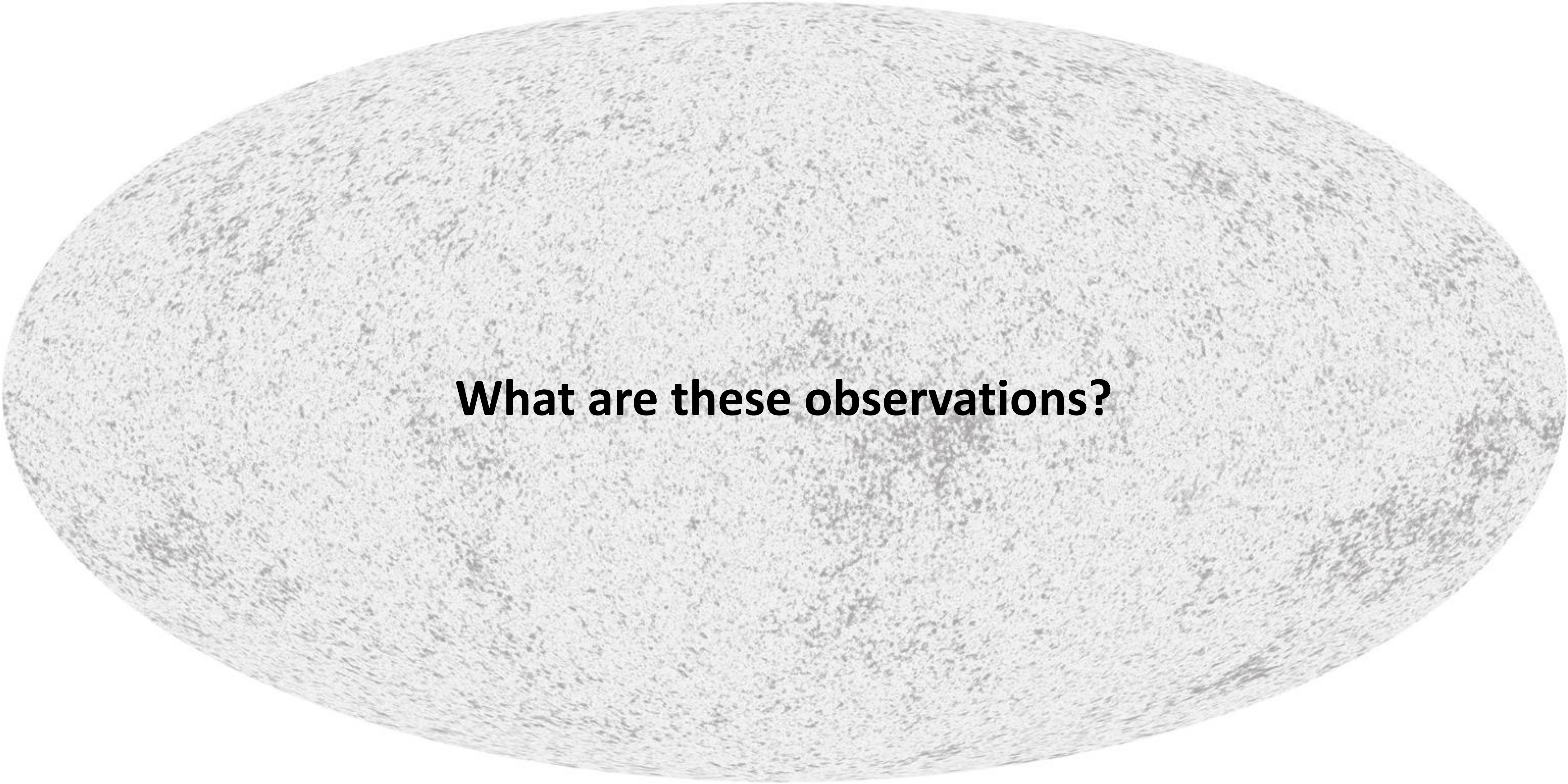
What made this possible?

Observations!

- To provide these a consistent theoretical framework, we required—
- A theory of spacetime and its interactions with matter (GR, deviations?)
- A theory of matter (Fields, particles, defects, etc.)

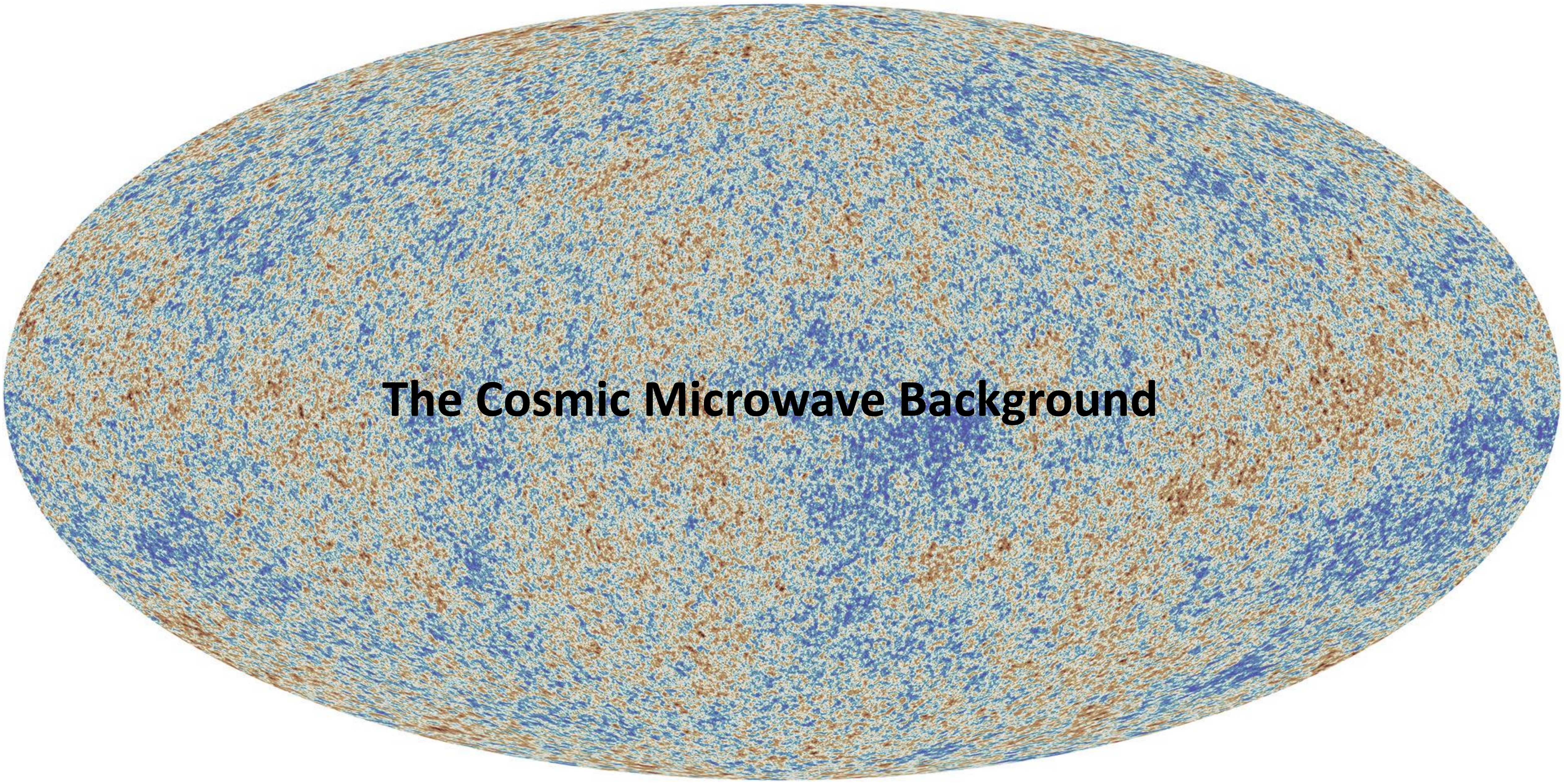
Observations!

- Symmetries: homogeneity, isotropy, thermal equilibrium (a statement of symmetry in state space: equipartition.)
- Luck. e.g. current model suggest at $t \sim 10^{12}$ y, $\lambda_{\mathrm{CMB}} > H_0^{-1}$ i.e. no electromagnetic evidence of the big bang (!)

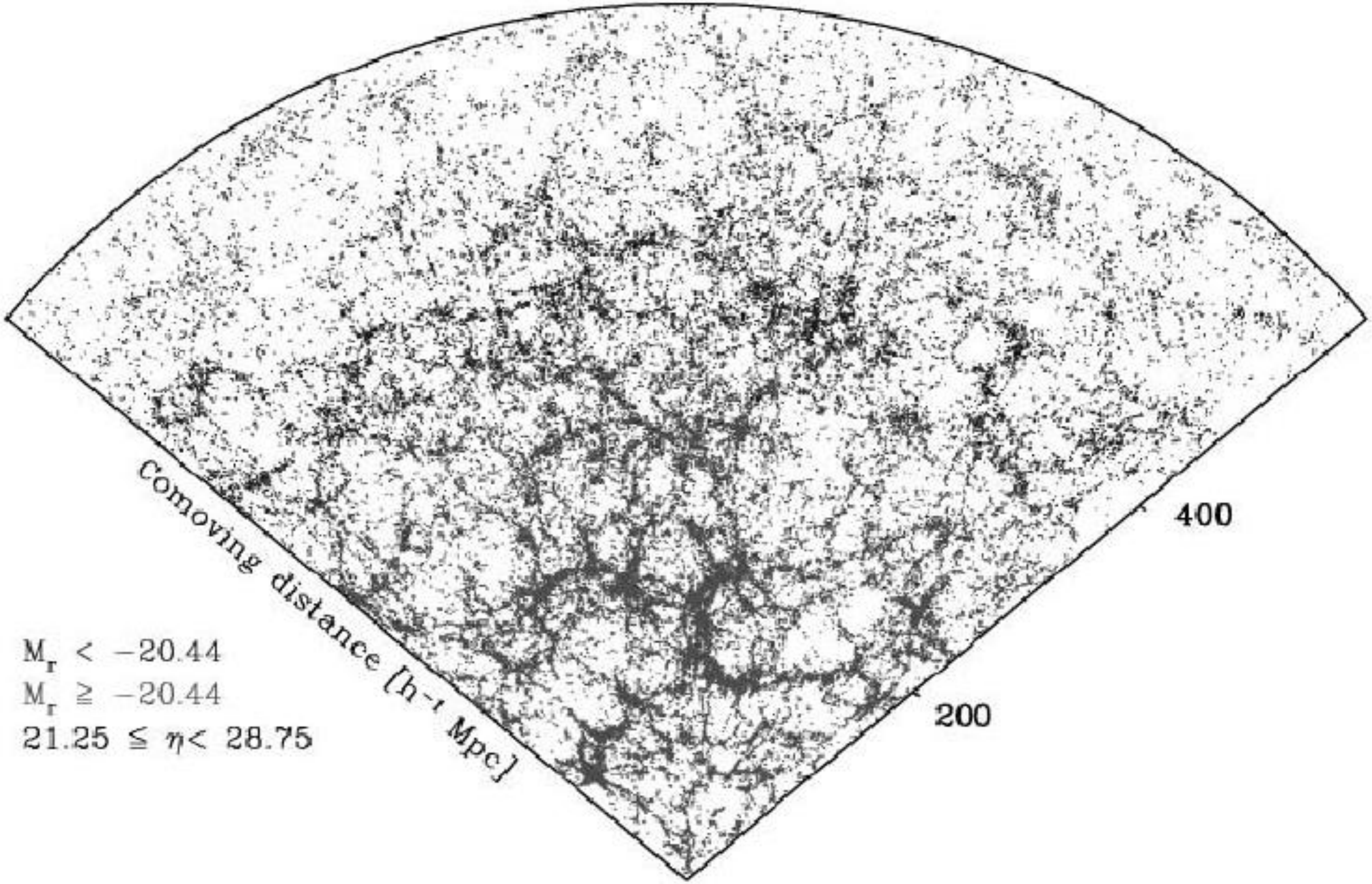


What are these observations?

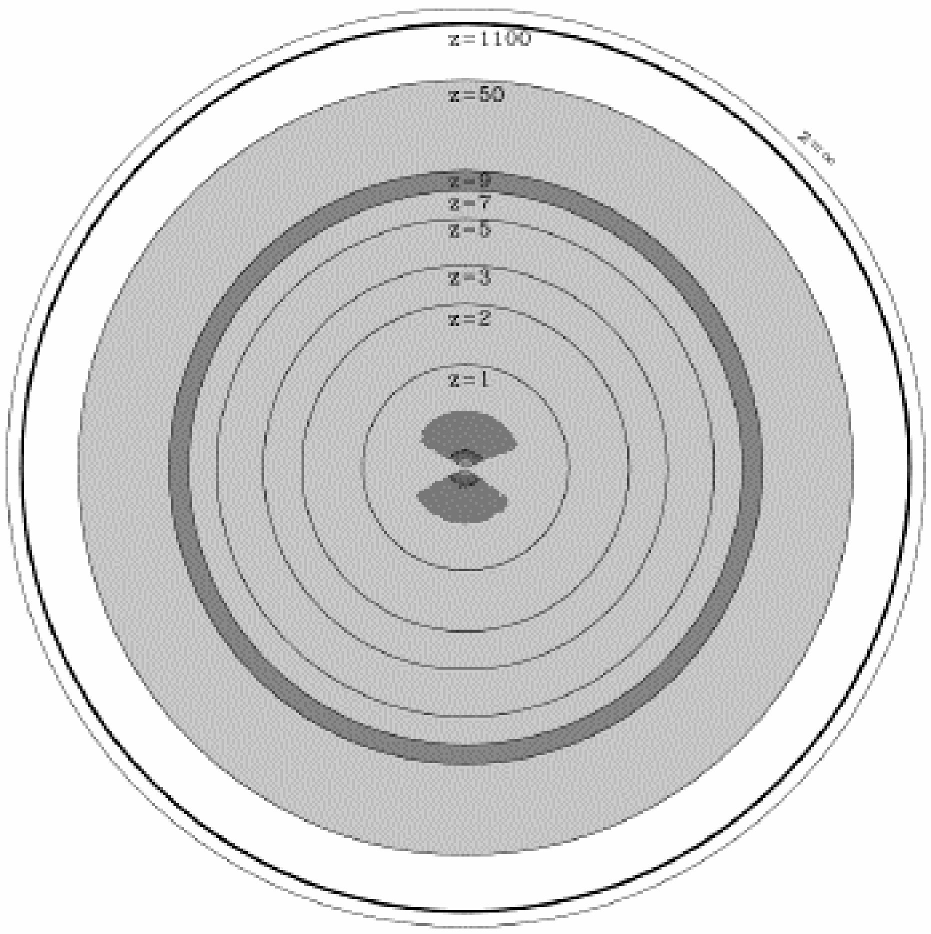
The Cosmic Microwave Background

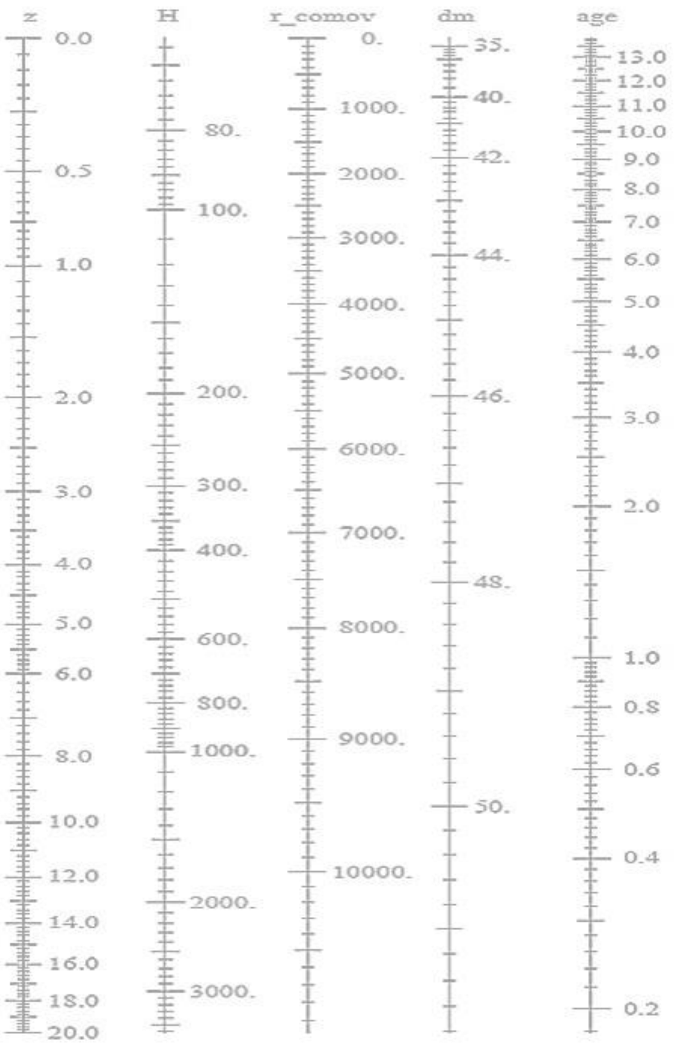


Large Scale Structure Surveys

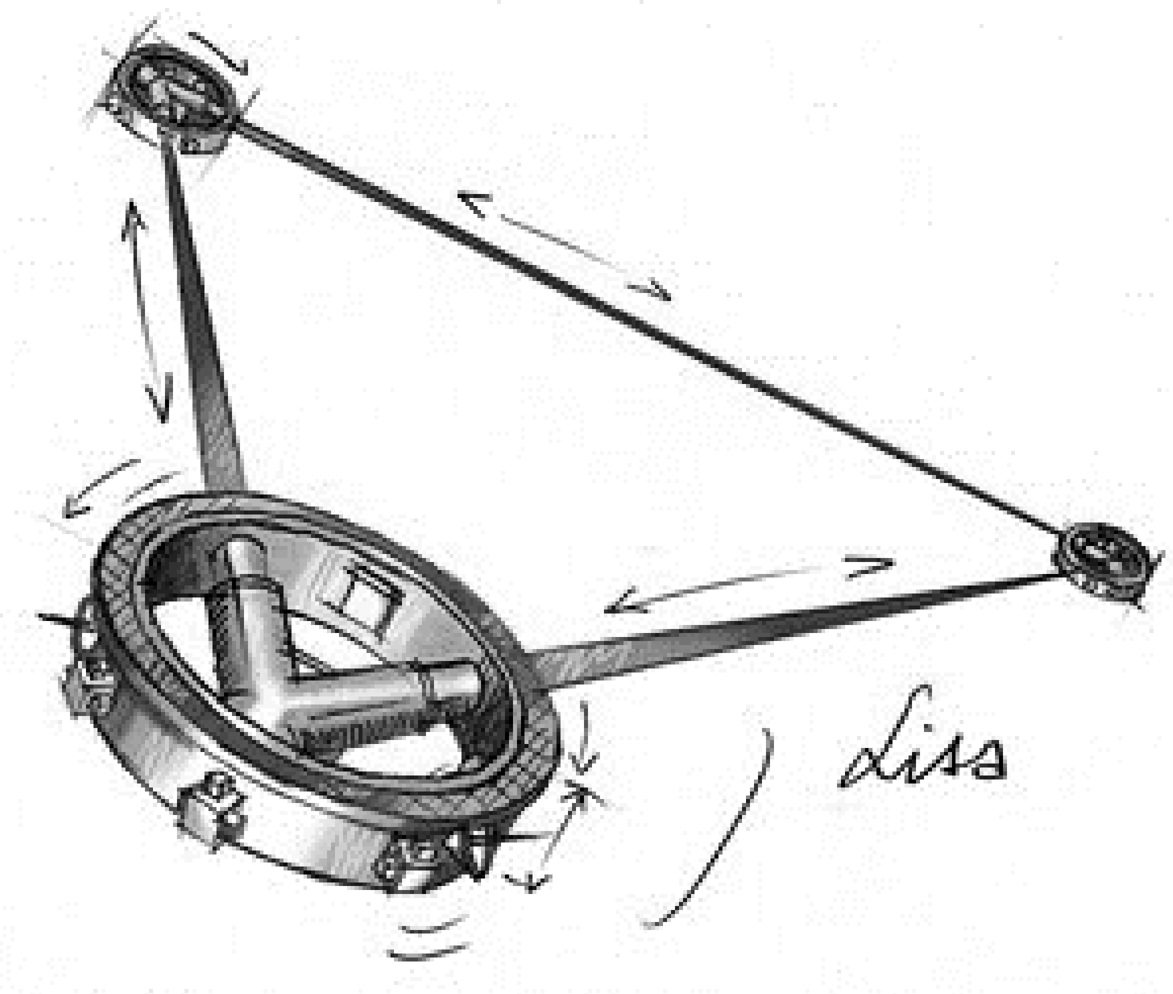


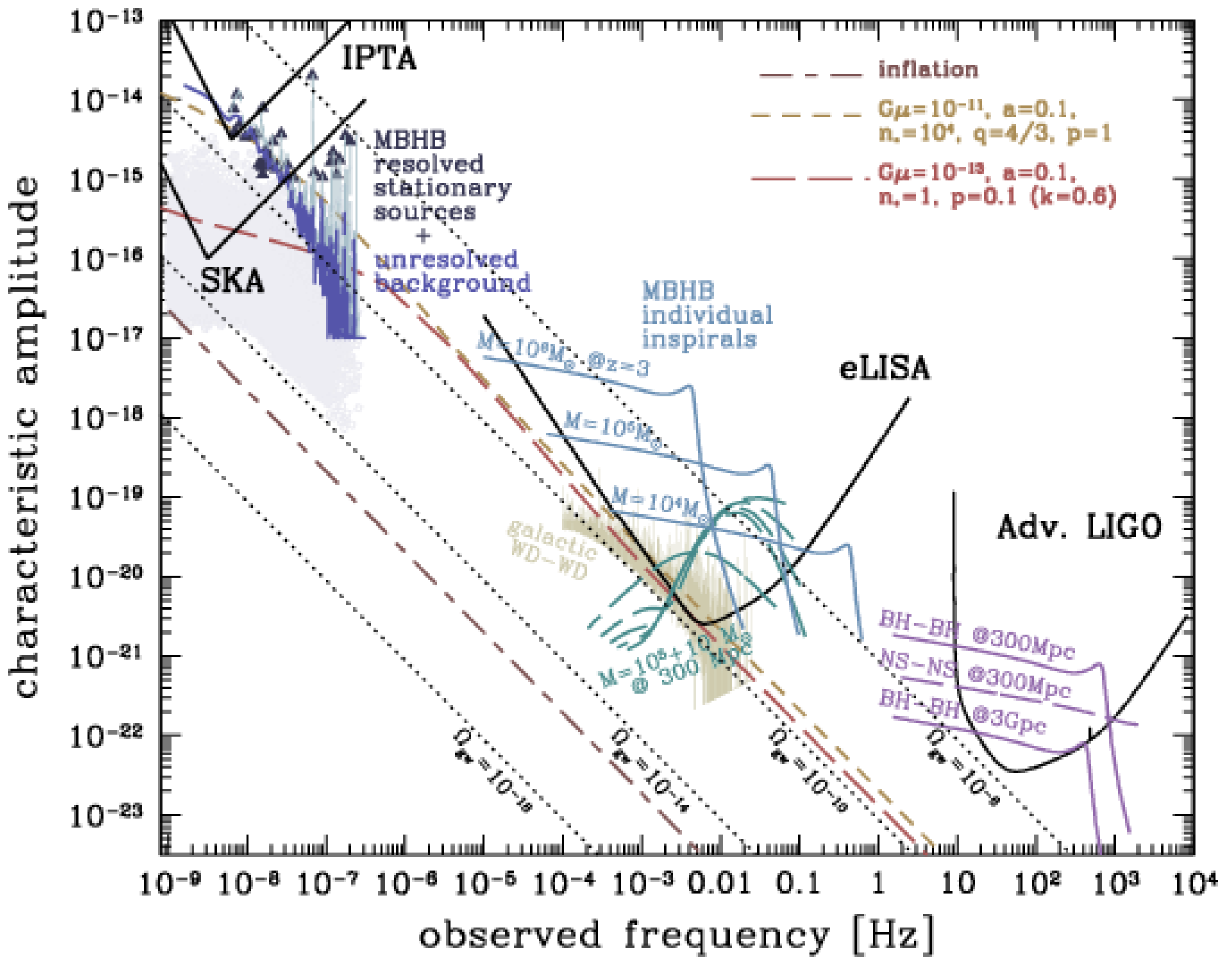
(The future: for things that don’t shine at us – 21 cm Tomography?)



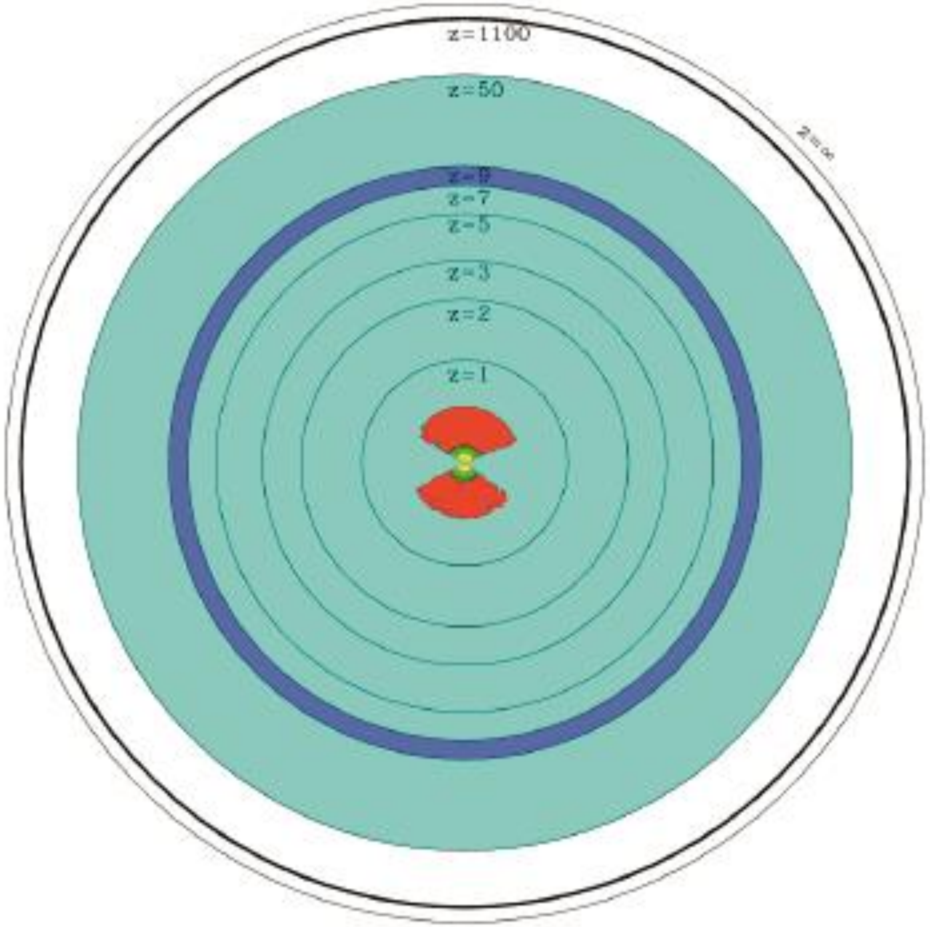


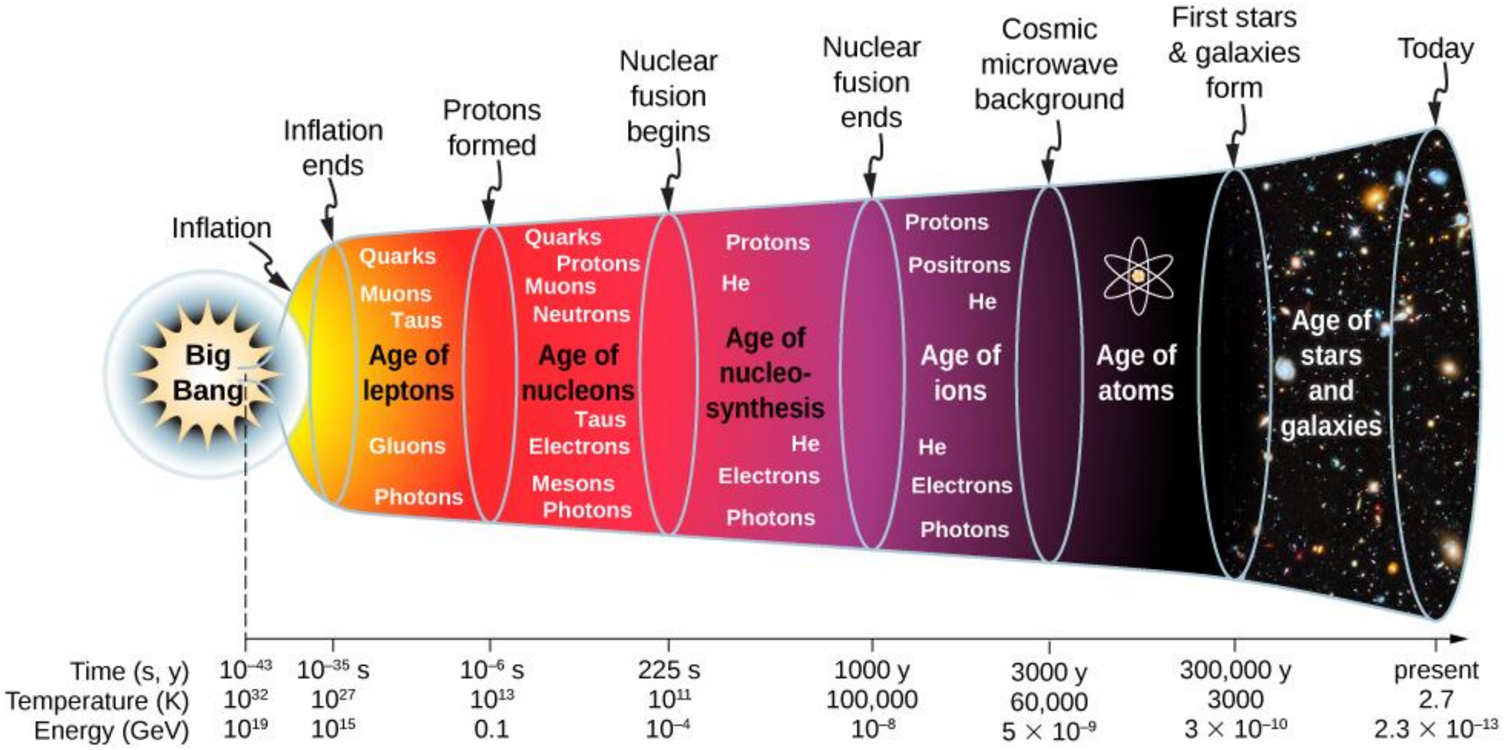
(The future cont: Gravitational Waves… cf. Tanja Hinderer's lectures)

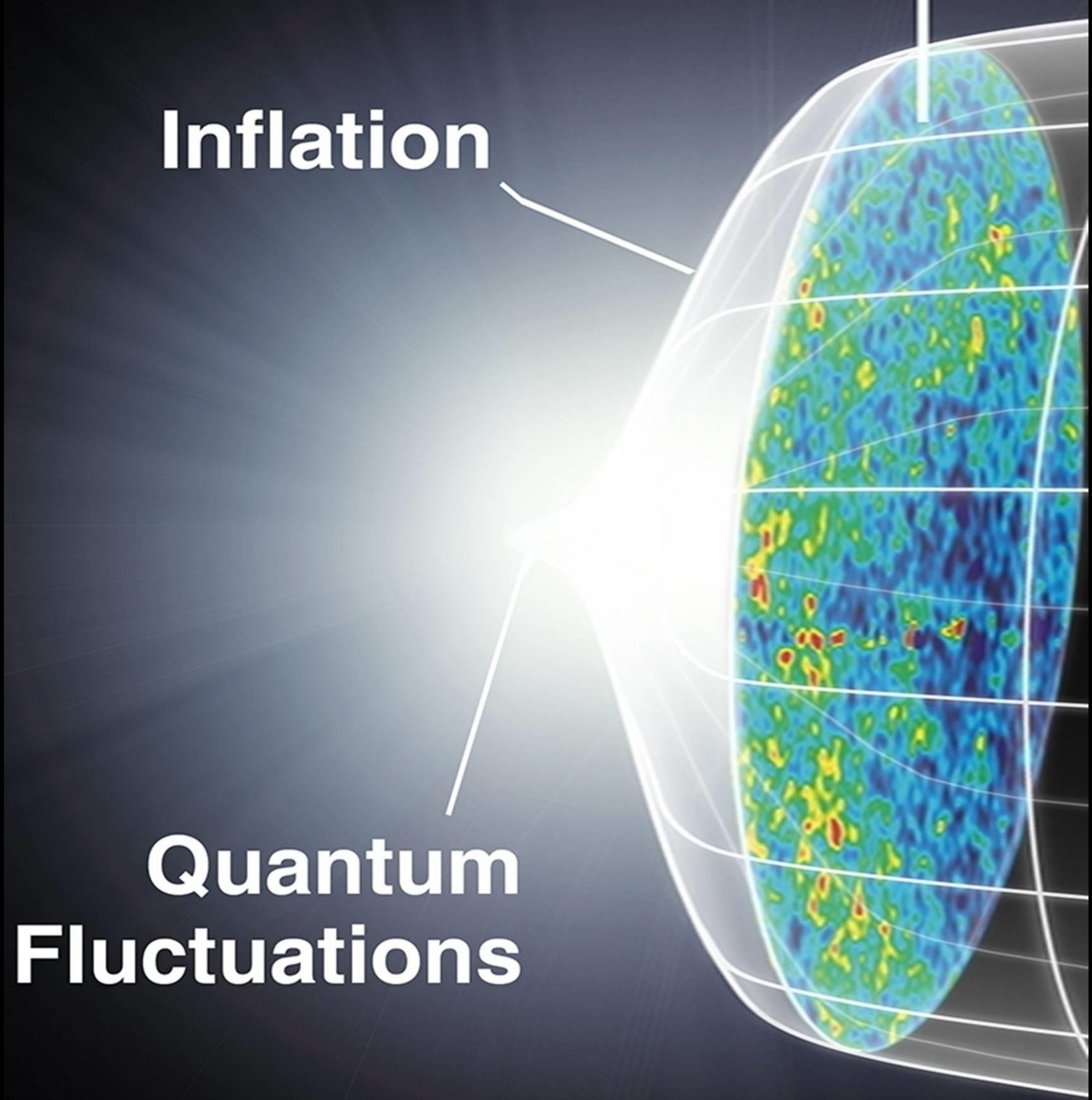


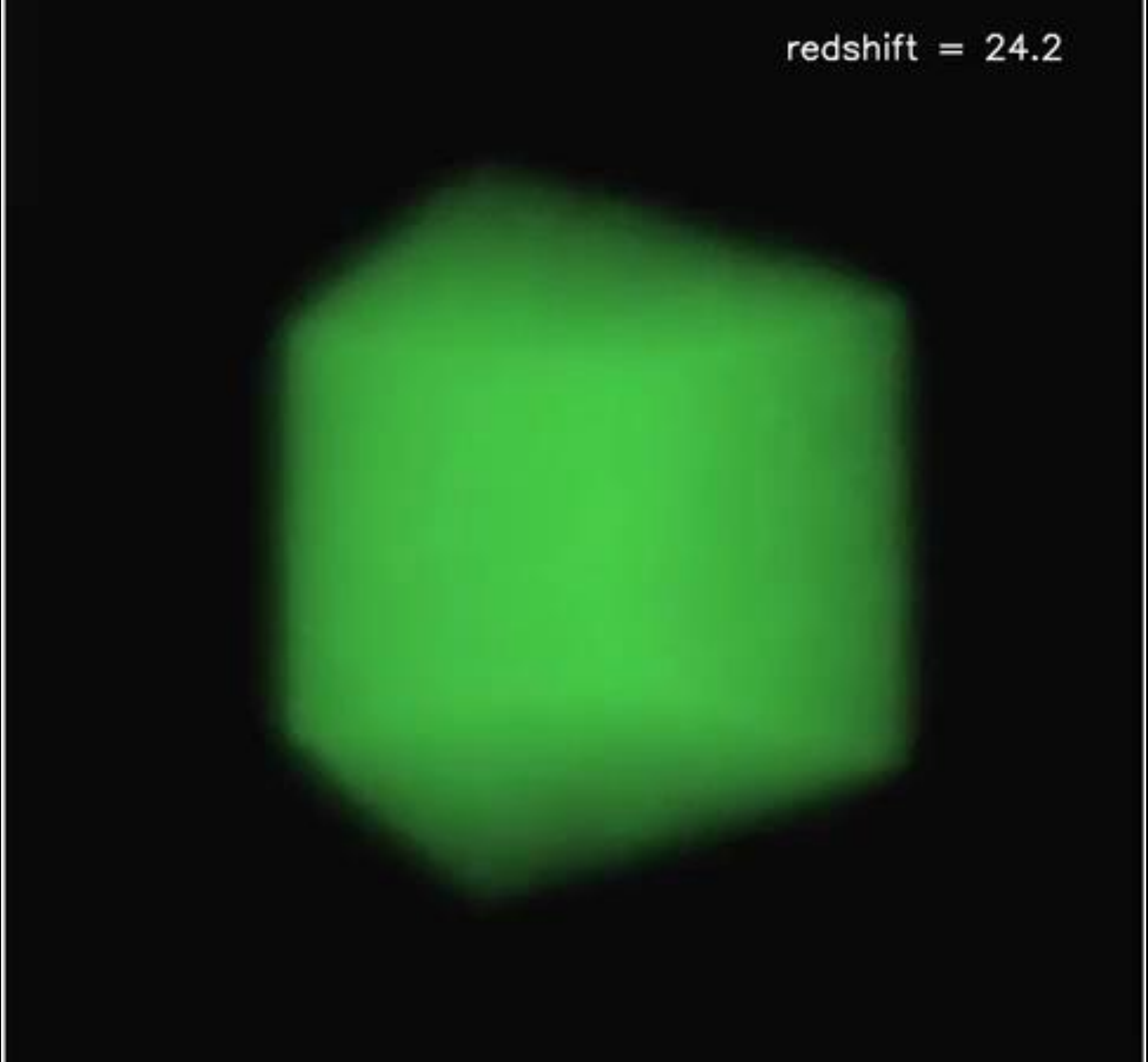


All observed structure is the result of gravitational collapse of initial `seed' perturbations…






Inflation
Quantum
Fluctuations


redshift = 24.2

The background – General Relativity + perfect fluids

$$G^{\mu}_{\nu} = 8\pi G_N T^{\mu}_{\nu}$$

spacetime curvature matter

$$S = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}R + \int d^4x\sqrt{-g}\mathcal{L}_M$$

metric tensor $ds^2 = g_{\mu\nu}(x)dx^{\mu}dx^{\nu}$

General Relativity – a conceptual crash course

metric tensor $ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu$

(Minkowski space: $ds^2 = \eta_{\mu\nu}dx^\mu dx^\nu = -dt^2 + dx^2 + dy^2 + dz^2$)

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General Relativity – a conceptual crash course

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`affine parameter'

General Relativity – a conceptual crash course

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$$S = -m\int ds = -m\int d\tau\sqrt{-g_{\mu\nu}\frac{dx^\mu}{d\tau}\frac{dx^\nu}{d\tau}}$$

`affine parameter'

Minkowski: $p_\mu = \frac{\delta\mathcal{L}}{\delta\dot{x}^\mu} = \frac{m}{\sqrt{1-\dot{\vec{x}}^2}}\frac{dx_\mu}{dt}$ e.o.m: $\frac{dp_\mu}{d\tau} = 0$

General Relativity – a conceptual crash course

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e.o.m on a curved background:

$$\tfrac{dx^\mu}{d\tau} := u^\mu; \quad \tfrac{du^\mu}{d\tau} + \Gamma^\mu_{\nu\lambda}u^\nu u^\lambda = 0$$

$$\Gamma^\mu_{\nu\lambda} := \tfrac{g^{\mu\kappa}}{2}\left(\tfrac{dg_{\kappa\nu}}{dx^\lambda} + \tfrac{dg_{\kappa\lambda}}{dx^\nu} - \tfrac{dg_{\nu\lambda}}{dx^\kappa}\right)$$

General Relativity – a conceptual crash course

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which is equivalent to $u^\mu \nabla_\mu u^\nu = 0$, where we have defined the *covariant derivative*:

$$\nabla_\mu u^\nu := \partial_\mu u^\nu + \Gamma^\nu_{\mu\lambda} u^\lambda$$

General Relativity – a conceptual crash course

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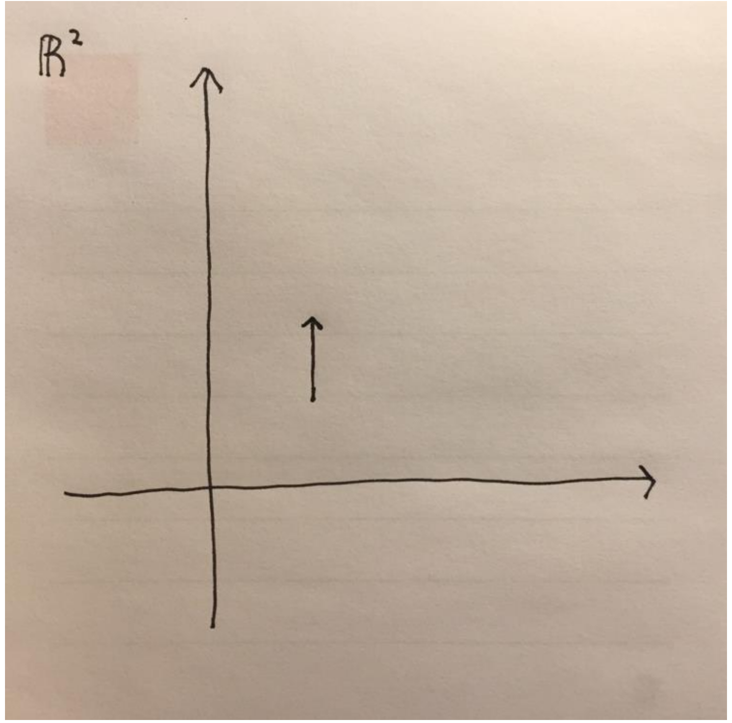
\`intrinsic change’ \`coordinate induced’

General Relativity – a conceptual crash course



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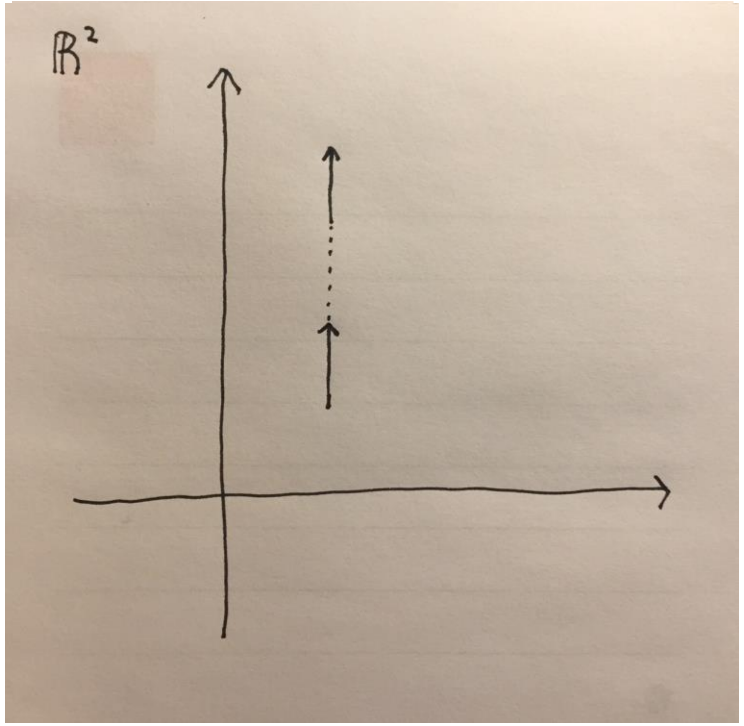
General Relativity – a conceptual crash course



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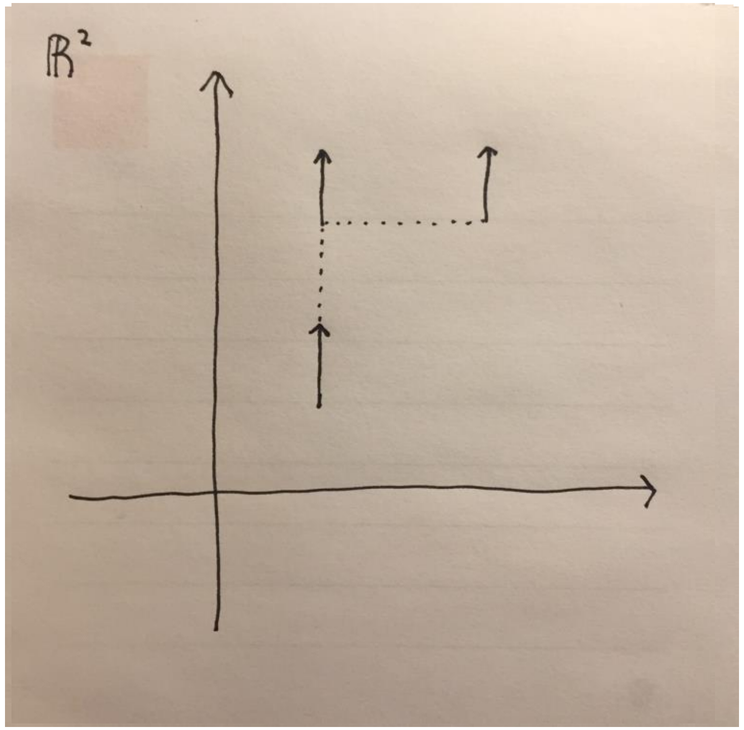

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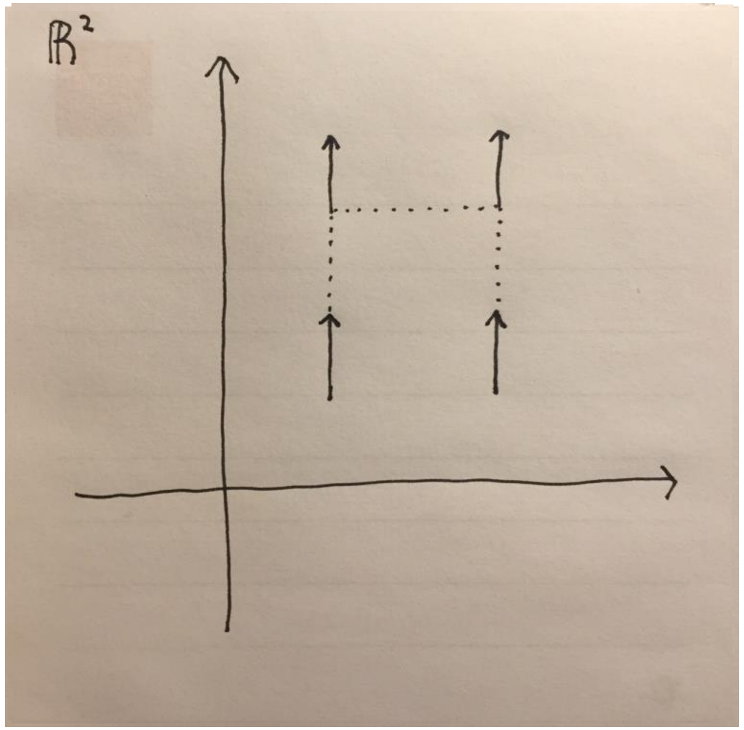
General Relativity – a conceptual crash course



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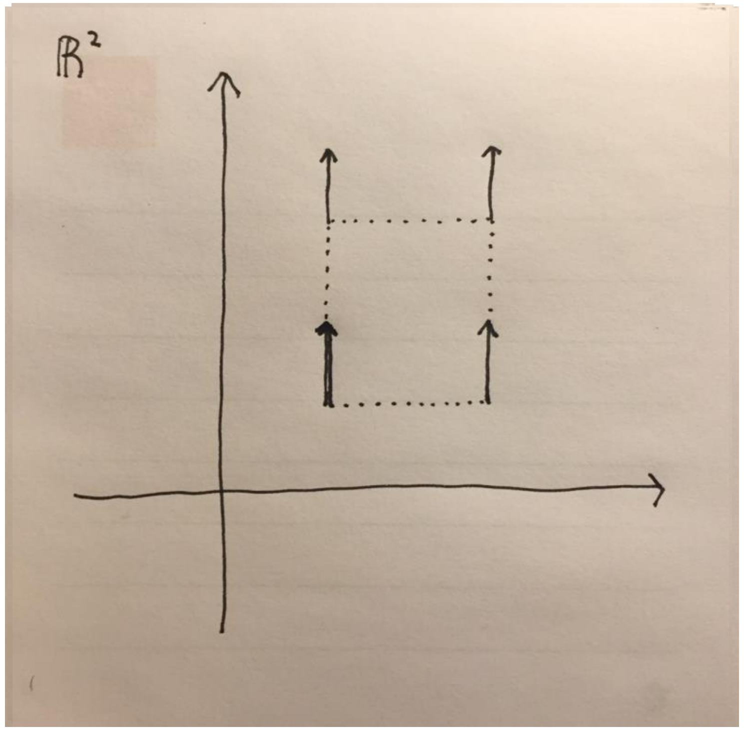
General Relativity – a conceptual crash course



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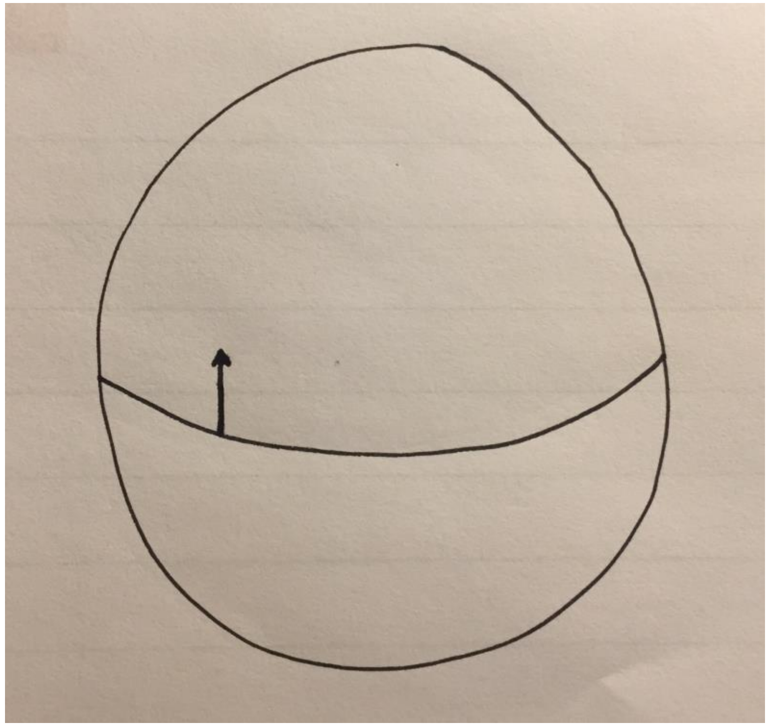

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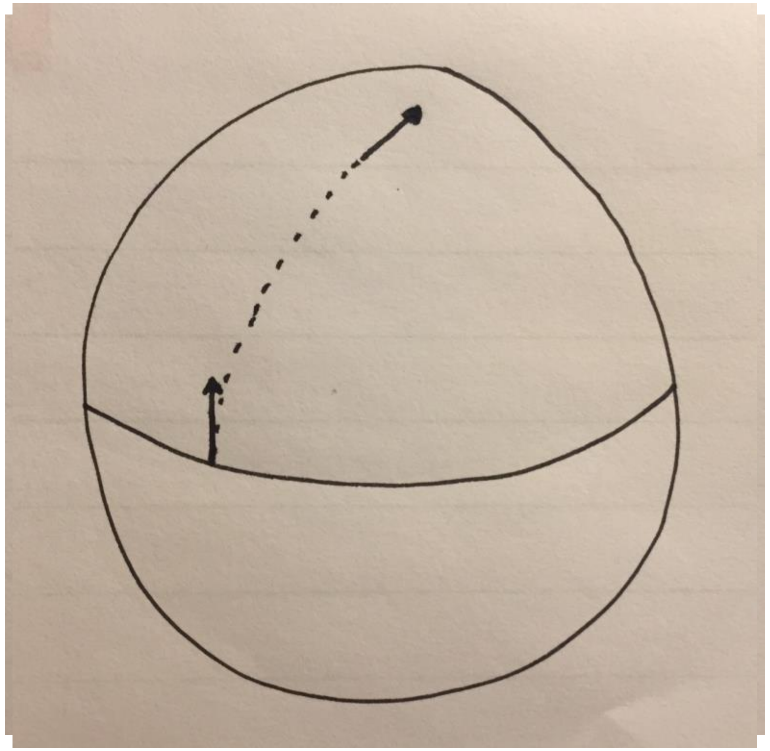

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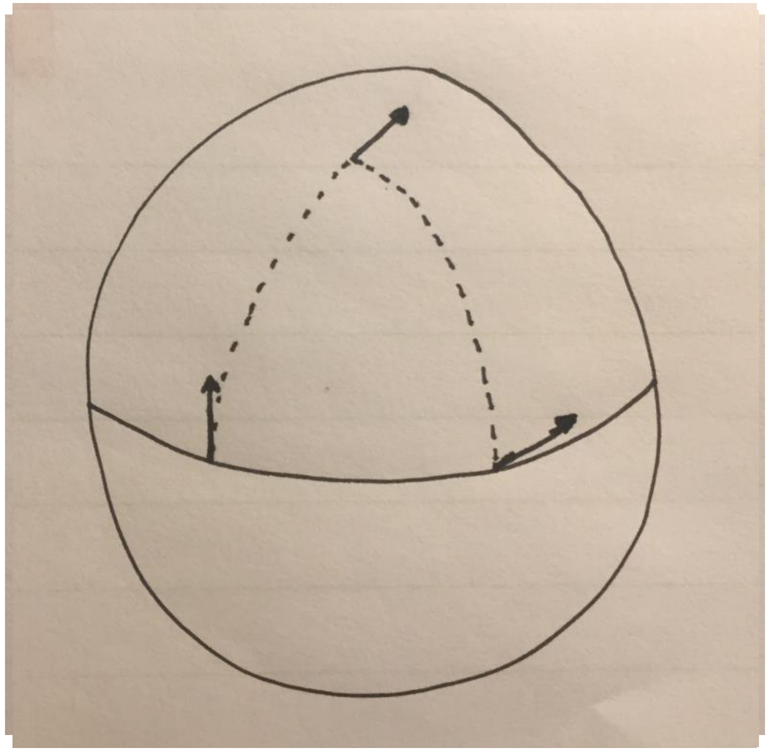

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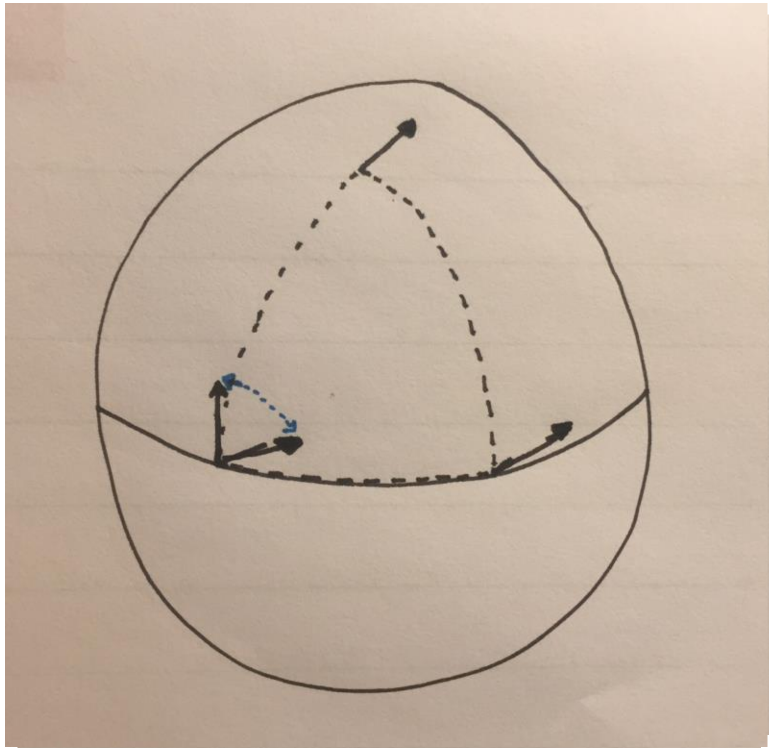

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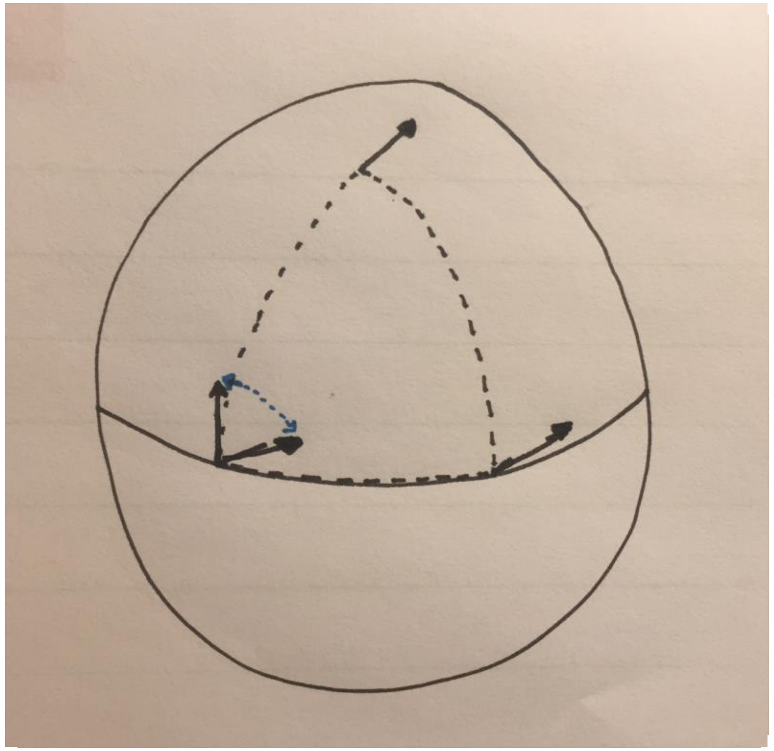
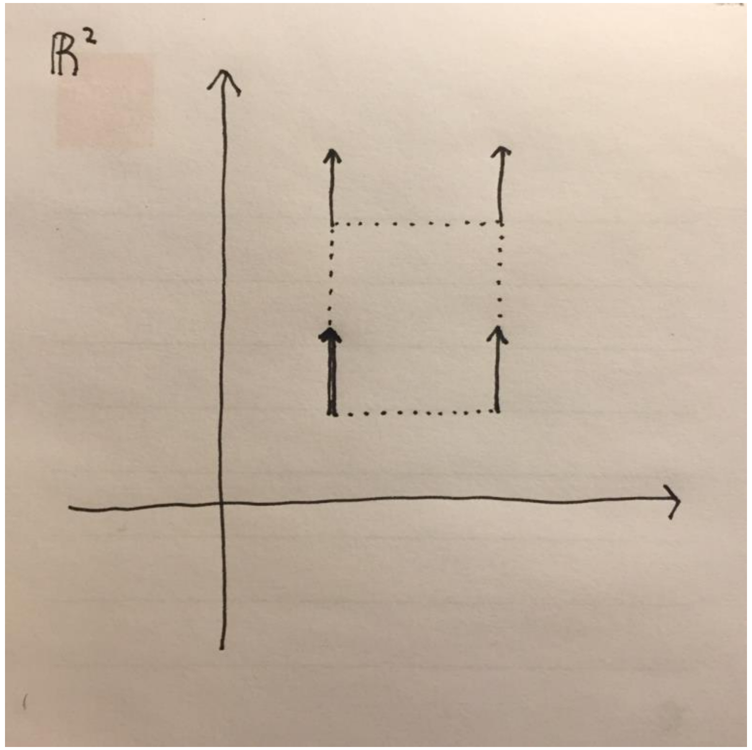
General Relativity – a conceptual crash course



A vector `parallel transported’ around a closed loop will come back to itself on a flat space. Not so on a `curved’ space…

General Relativity – a conceptual crash course



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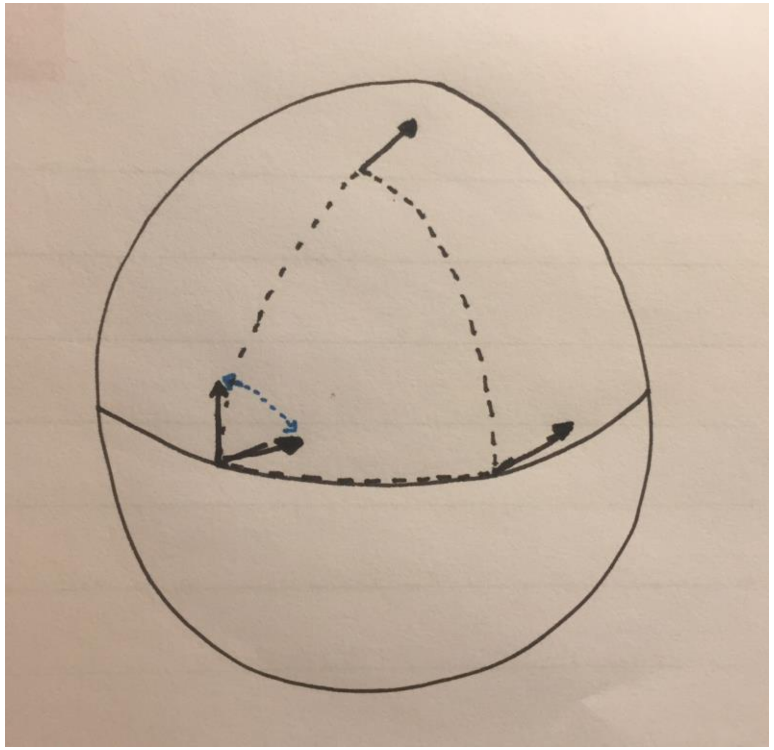
General Relativity – a conceptual crash course



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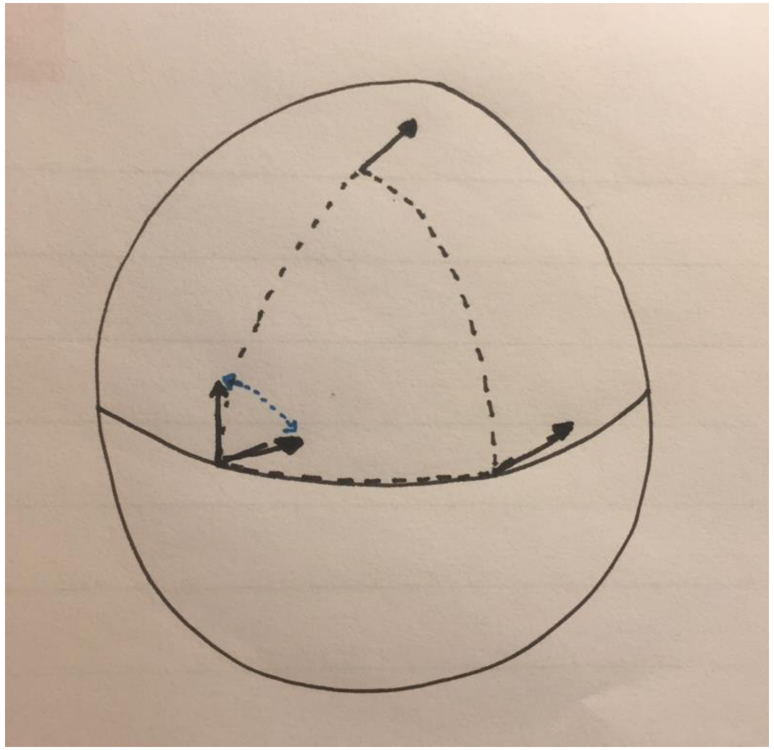
$$\left(\nabla_\lambda \nabla_\mu - \nabla_\mu \nabla_\lambda\right) u^\nu = ?$$

General Relativity – a conceptual crash course



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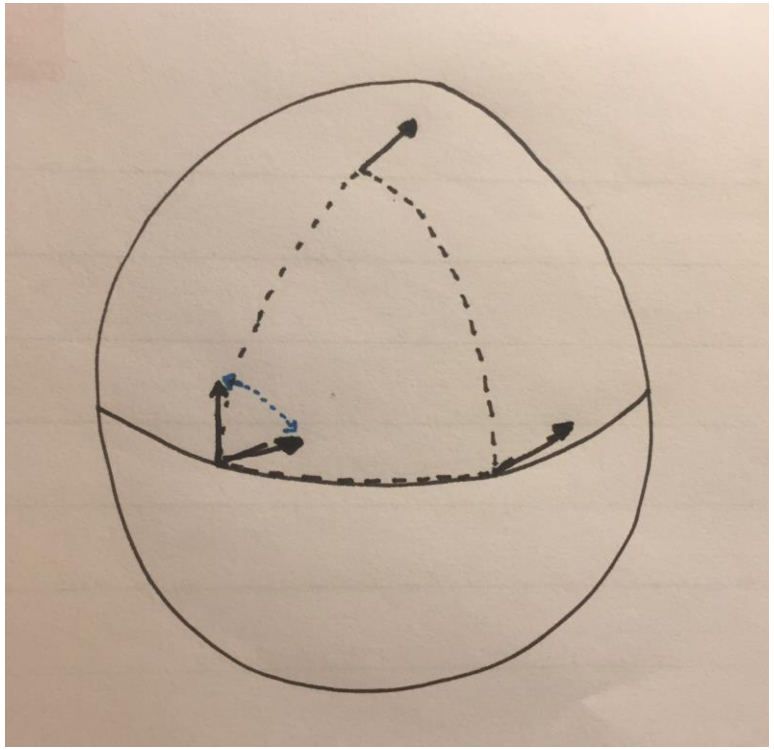
$$\left(\nabla_\lambda \nabla_\mu - \nabla_\mu \nabla_\lambda\right) u^\nu := R^\nu_{\rho\lambda\mu} u^\rho$$

Riemann curvature tensor

General Relativity – a conceptual crash course



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Riemann curvature tensor

$$R^\nu_{\rho\lambda\mu} = \partial_\lambda \Gamma^\nu_{\rho\mu} - \partial_\mu \Gamma^\nu_{\rho\lambda} + \Gamma^\nu_{\kappa\lambda}\Gamma^\kappa_{\rho\mu} - \Gamma^\nu_{\kappa\mu}\Gamma^\kappa_{\rho\lambda}$$

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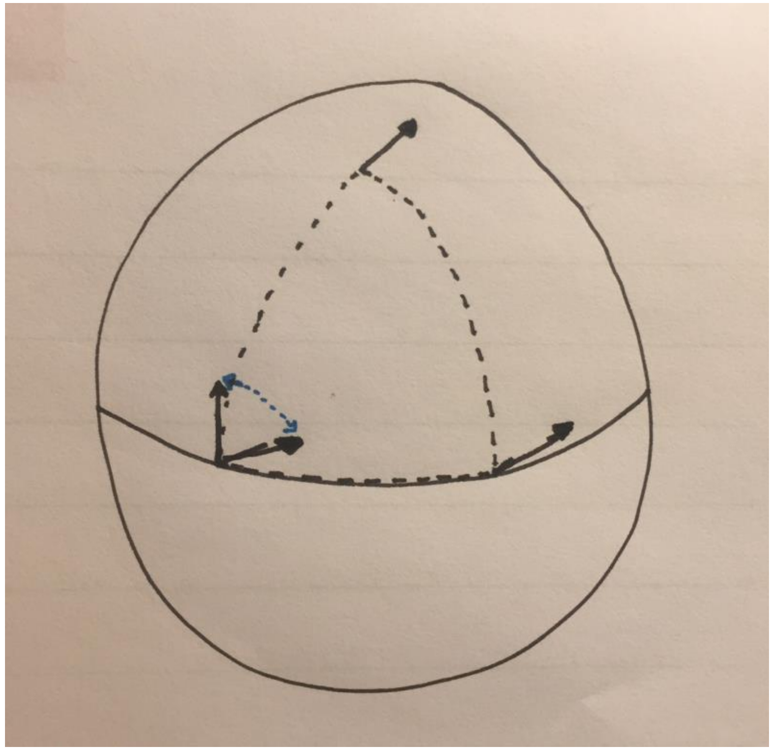
General Relativity – a conceptual crash course



$$[\nabla_\lambda, \nabla_\mu]\, u^\nu := R^\nu_{\rho\lambda\mu} u^\rho$$

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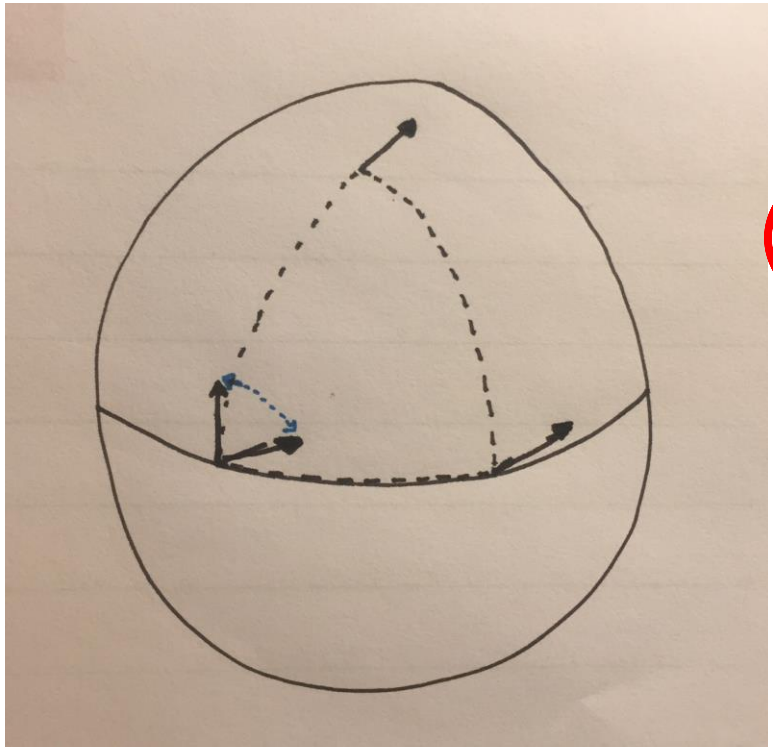
cf. electromagnetism:

$$D_\mu := \partial_\mu - ieA_\mu$$

$$[D_\mu, D_\nu] = -ie\left(\partial_\mu A_\nu - \partial_\nu A_\mu\right) = -ieF_{\mu\nu}$$

General Relativity – a conceptual crash course



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Field strengths!

$$D_\mu := \partial_\mu - ieA_\mu$$

$$[D_\mu, D_\nu] = -ie\left(\partial_\mu A_\nu - \partial_\nu A_\mu\right) = -ieF_{\mu\nu}$$

General Relativity <u>is</u> a gauge theory (cf. John Donoghue's lectures)

Electromagnetism: $\mathcal{L}_{\mathrm{EM}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$

$$\Gamma^{\mu}_{\nu\lambda} := \frac{g^{\mu\kappa}}{2} \left(\frac{dg_{\kappa\nu}}{dx^{\lambda}} + \frac{dg_{\kappa\lambda}}{dx^{\nu}} - \frac{dg_{\nu\lambda}}{dx^{\kappa}} \right)$$

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Gravity: $\mathcal{L}_{\mathrm{GR}} \stackrel{?}{=} [M]^2 g^{\rho\mu} R^{\nu}_{\rho\nu\mu}$

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Gravity: $\mathcal{L}_{\mathrm{GR}} = \frac{1}{16\pi G_N} g^{\rho\mu} R^{\nu}_{\rho\nu\mu} := \frac{1}{16\pi G_N} R$

Ricci scalar

Gravity is an effective theory (cf. John and Cliff Burgess' lectures)

Electromagnetism:

$$\mathcal{L}_{\rm EM} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{c_1}{M^4}\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \tfrac{c_2}{M^4}\left(\epsilon^{\mu\nu\lambda\beta}F_{\mu\nu}F^{\lambda\beta}\right)^2 + \ldots$$

Gravity: $\mathcal{L}_{\rm GR} = \frac{1}{16\pi G_N}R + c_1 R^2 + c_2 R^{\mu}_{\nu\lambda\beta}R_{\mu}^{\nu\lambda\beta} + \ldots$

$$8\pi G_N := \tfrac{1}{M_{\rm pl}^2}$$

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Electromagnetism:

$$\mathcal{L}_{\mathrm{EM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{c_1}{M^4}\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \frac{c_2}{M^4}\left(\epsilon^{\mu\nu\lambda\beta}F_{\mu\nu}F^{\lambda\beta}\right)^2 + \ldots$$

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$$8\pi G_N := \frac{1}{M_{\mathrm{pl}}^2}$$

(Apologies for the hit and run treatment – an excellent, no-nonsense introduction to GR can be found in *Spacetime and Geometry* by Sean Carroll. A more thorough mathematical intro can be found in *General Relativity* by R. M. Wald)

The background – General Relativity + perfect fluids

$$S = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}R + \int d^4x\sqrt{-g}\mathcal{L}_M$$

$$R^{\lambda}_{\mu\lambda\nu} - \frac{1}{2}g_{\mu\nu}R := G_{\mu\nu} = 8\pi G_N T^{\mu}_{\nu}$$

$$ds^2 = g_{\mu\nu}(x)dx^{\mu}dx^{\nu}$$

want to solve for the geometry given a particular matter content.

The background – General Relativity + perfect fluids

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$$T^{\mu}_{\nu} \equiv \langle T^{\mu}_{\nu}\rangle$$

What is the state $|\Psi\rangle$ that defines this expectation value?

The background – General Relativity + perfect fluids

On the equivalence between the Boltzmann equation and classical field theory at large occupation numbers

A.H. Mueller [a], D.T. Son [b]

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[b] *Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550, USA*

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The dynamics of any field theory at large enough occupation number (e.g. in $\lambda\phi^4$ theory, with $\lambda N_k \ll 1$ reduces to kinetic theory. For, $k \ll (\rho/m)^{1/3}$ this is hydrodynamics*.

*(Non)-equilibrium hydro/ kinetic theory $\longleftrightarrow$ (non)-equilibrium QFT at large occupation.

The history of the Universe in a line:

$$G_{\mu\nu} = 8\pi G_N \langle T^{\mu}_{\nu} \rangle$$

$$\widehat{\rho}_{\Psi} : |\phi\rangle\langle\phi| \rightarrow \sum_i e^{-\beta E_i} |E_i\rangle\langle E_i| \rightarrow \sum_a c_a |n_a\rangle\langle n_a|; \quad (n_i \gg 1)$$

e.g. $c_a \sim e^{-\beta_a E_a}$ at freeze-out

Inflation

↓

(p)re-heating to a thermalized universe

↓

perfect fluid (radiation matter domination)

The background – ISO(3) invariance (homogeneity, Isotropy)

$$G_{\mu\nu} = 8\pi G_N \langle T^{\mu}_{\nu} \rangle$$

$$T^{\mu}_{\nu} = (\rho + P) u^{\mu} u_{\nu} + P g_{\mu\nu}$$

u^{μ} is the four velocity vector of a fluid element, can adapt our coordinate system such that there is no momentum flux across spatial slices (i.e. u^{μ} defines the time direction).

$$T^{\mu}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$$

$$ds^2 = -dt^2 + a^2(t) \left(dx^2 + dy^2 + dz^2 \right)$$

The background – inflation

$$G_{\mu\nu} = 8\pi G_N \langle T^{\mu}_{\nu} \rangle \qquad T^{\mu}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$$

$$ds^2 = -dt^2 + a^2(t)\left(dx^2 + dy^2 + dz^2\right)$$

$$\rho = \frac{\dot{\phi}^2}{2} + V(\phi), \;\; p = \frac{\dot{\phi}^2}{2} - V(\phi)$$

$\rho \approx -p$ if $\frac{\dot{\phi}^2}{2} \ll V(\phi)$

$$\frac{3\dot{a}^2}{a^2} = \frac{1}{M_{\mathrm{pl}}^2}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right) \approx \frac{V(\phi)}{M_{\mathrm{pl}}^2}$$

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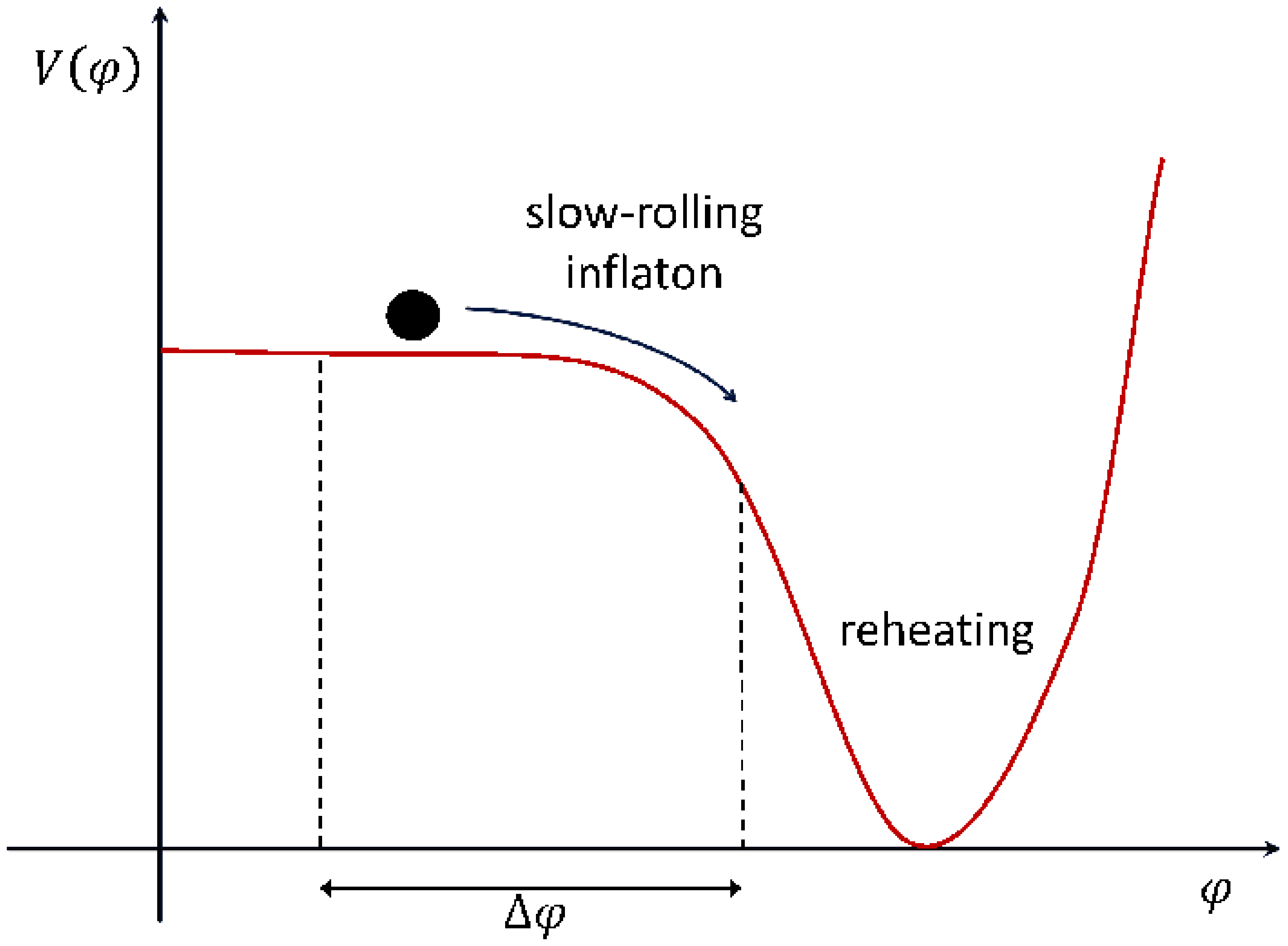
$$\frac{3\dot{a}^2}{a^2} := 3H^2 = \frac{1}{M_{\rm pl}^2}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right) \approx \frac{V(\phi)}{M_{\rm pl}^2}$$

$$a(t) \propto e^{Ht} \quad \text{if} \quad \epsilon := \frac{\dot{\phi}^2}{2H^2M_{\rm pl}^2}, \eta := \frac{\dot{\epsilon}}{H\epsilon} \ll 1$$

The background – inflation



The background – radiation, matter domination

$$p = w\rho\,,\ \nabla_\mu T^\mu_0 \to \dot\rho + 3H(\rho + p) = 0$$

$$\rho \propto \frac{1}{a^{3(1+w)}}$$

$a(t) \propto t^{1/2}$ if $w = 1/3$ (radiation domination)
$a(t) \propto t^{2/3}$ if $w = 0$ (matter domination)

The background – General Relativity + perfect fluids

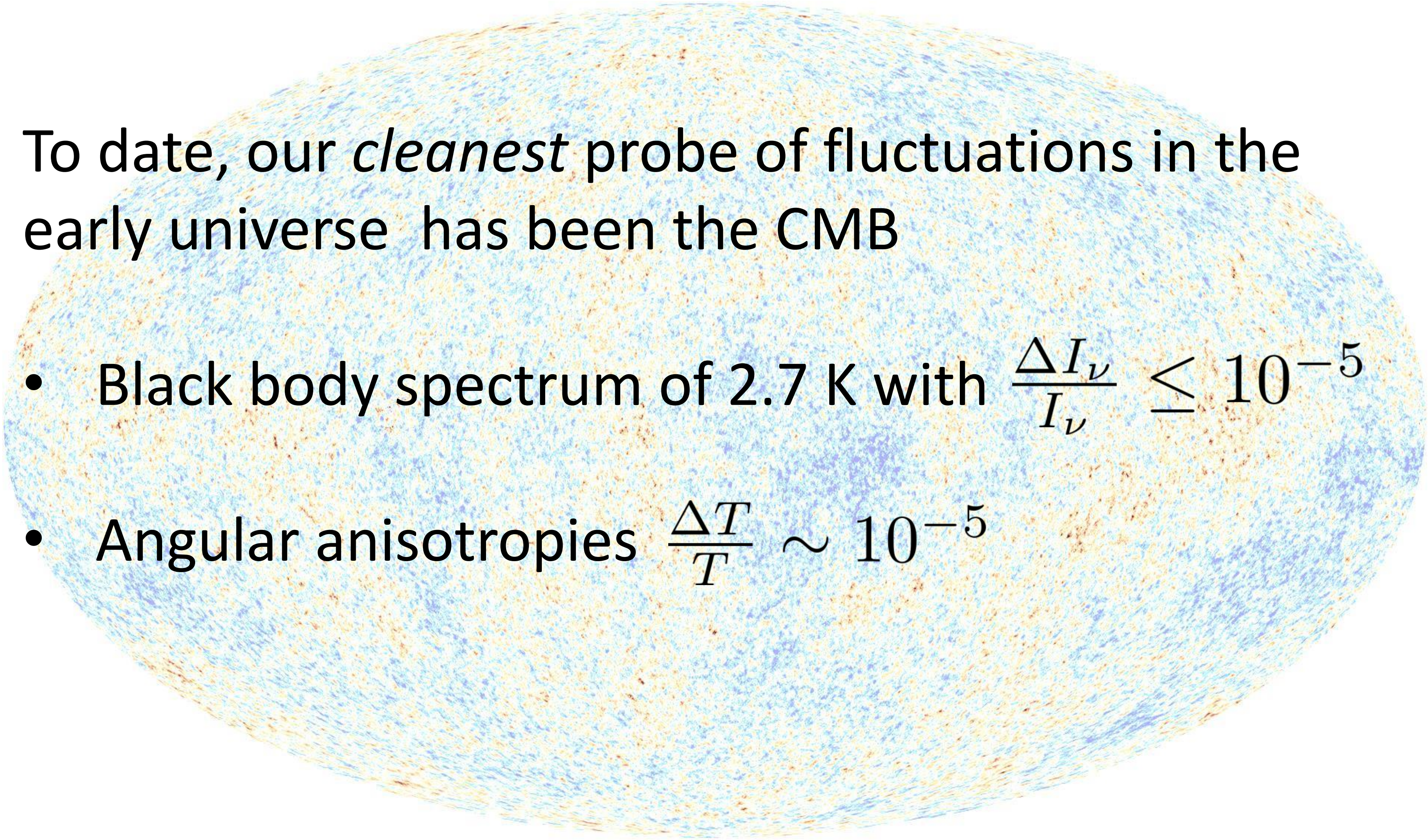
$$G_{\mu\nu} = 8\pi G_N T^{\mu}_{\nu}$$

Inflation, thermalization, radiation domination, matter domination, dark energy domination…

Perturbations – from quantum fields to galaxies

$$\delta G_{\mu\nu} = 8\pi G_N \delta T^{\mu}_{\nu}$$

perturbations: $g_{\mu\nu} = g^{(0)}_{\mu\nu} + \delta g_{\mu\nu}$



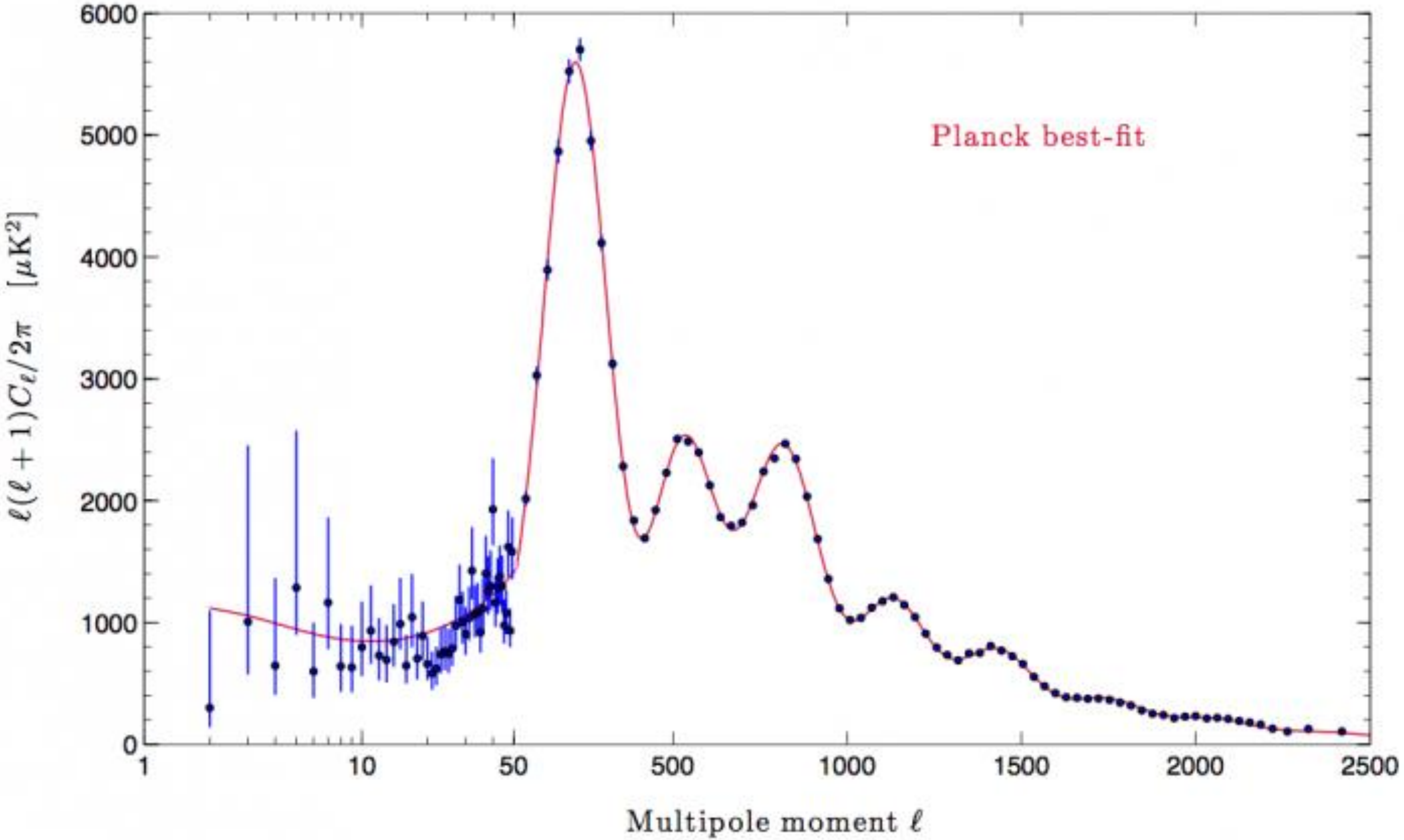
To date, our *cleanest* probe of fluctuations in the early universe has been the CMB

- Black body spectrum of 2.7 K with $\frac{\Delta I_\nu}{I_\nu} \leq 10^{-5}$
- Angular anisotropies $\frac{\Delta T}{T} \sim 10^{-5}$

What is the information content of the CMB?

- Temperature (T) and polarization (E,B) in each direction $\leftrightarrow 10^6$ `pixels' in the sky.

- Spectrum of incident photons in a given direction (new information only w/ deviations from blackbody).

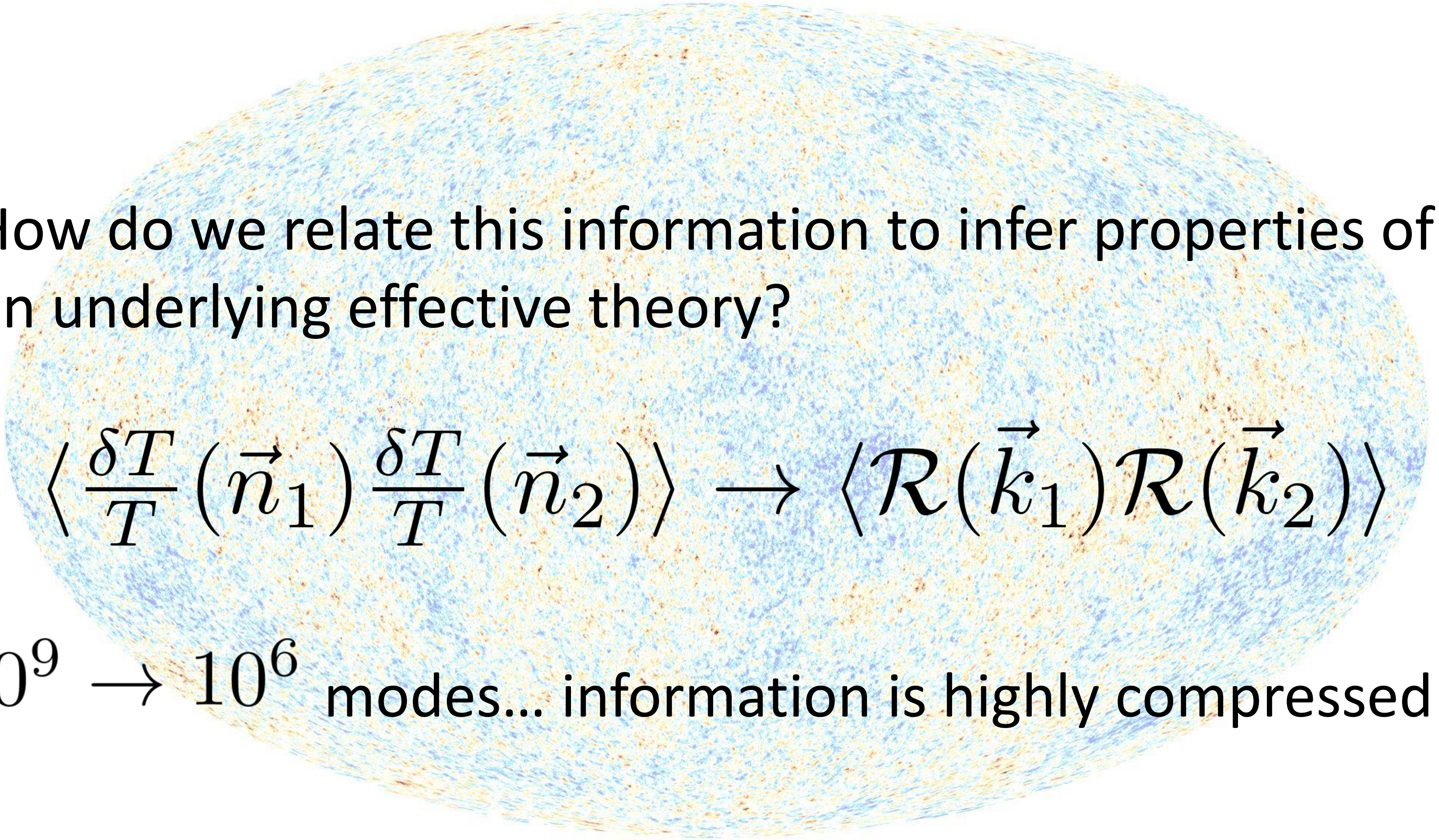


6000
5000
4000
3000
2000
1000
0
$\ell(\ell+1)C_\ell/2\pi \quad [\mu K^2]$
Planck best-fit
1
10
50
500
1000
1500
2000
2500
Multipole moment ℓ

What is the information content of the CMB?

- For T, radio sources and (SZ) clusters start to dominate at $\ell \sim 2500$
- For E, foregrounds subdominant until $\ell \sim 5000$
- Damping tail to be measured more precisely (SPTPol, ACTPol, CMB S4…)
- Forecast $\sum_\nu m_\nu \sim 0.05 \text{ eV}$
- Cosmological measurement of a BSM parameter?

$$\mathcal{L} \supset \frac{H^\dagger H}{\Lambda} \bar{\psi}\psi; \quad \Lambda \sim 10^{16} \text{GeV}$$



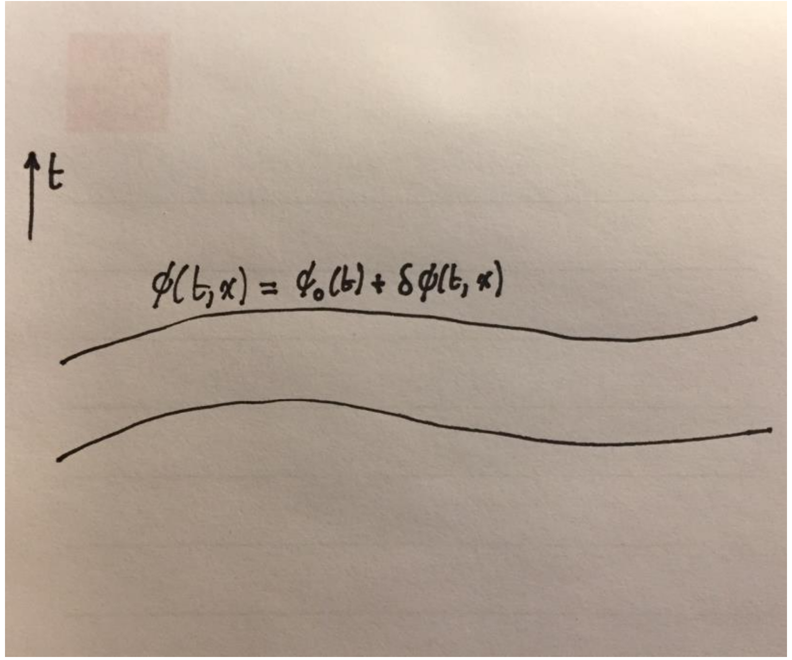
How do we relate this information to infer properties of an underlying effective theory?

$$\langle \frac{\delta T}{T}(\vec{n}_1)\frac{\delta T}{T}(\vec{n}_2)\rangle \to \langle\mathcal{R}(\vec{k}_1)\mathcal{R}(\vec{k}_2)\rangle$$

$10^9 \to 10^6$ modes… information is highly compressed!

How do we relate this information to infer properties of an underlying effective theory?

$$\mathcal{L}_{\rm tot} = \frac{M_{\rm pl}^2}{2} R + ... + \mathcal{L}(\phi, \nabla\phi, \nabla^2\phi, ...)$$



$$\phi(x,t) = \phi_0(t) + \delta\phi(t,x)$$

$$t \;\rightarrow\; t + \pi$$

$$\phi_0 + \delta\phi(t,x) \rightarrow \phi_0 + \delta\phi(t,x) - \dot{\phi}_0 \pi \equiv \phi_0(t)$$

$$\mathrm{d}s^2 = -N^2 \mathrm{d}t^2 + h_{ij}(\mathrm{d}x^i + N^i \mathrm{d}t)(\mathrm{d}x^j + N^j \mathrm{d}t)$$

$$h_{ij} = a^2(t) e^{2\mathcal{R}} \delta_{ij}$$

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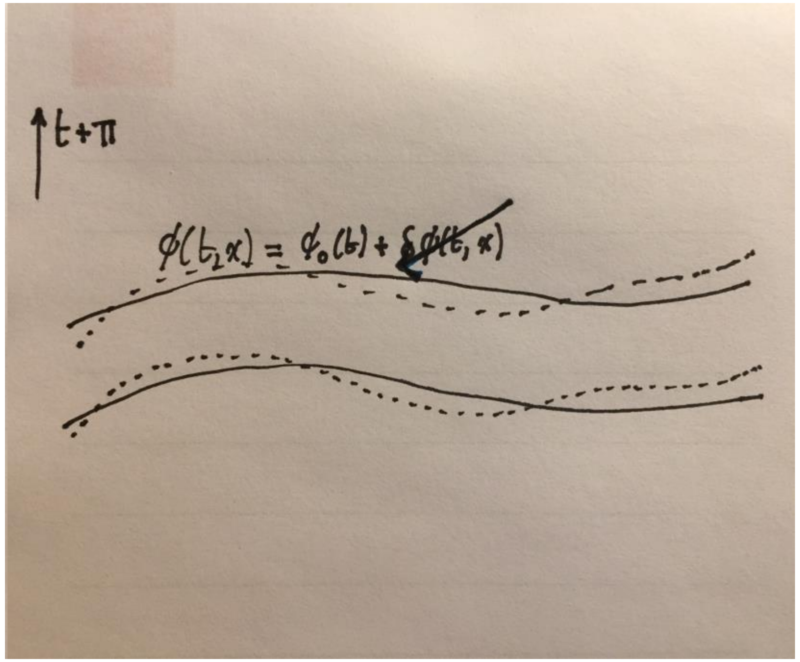

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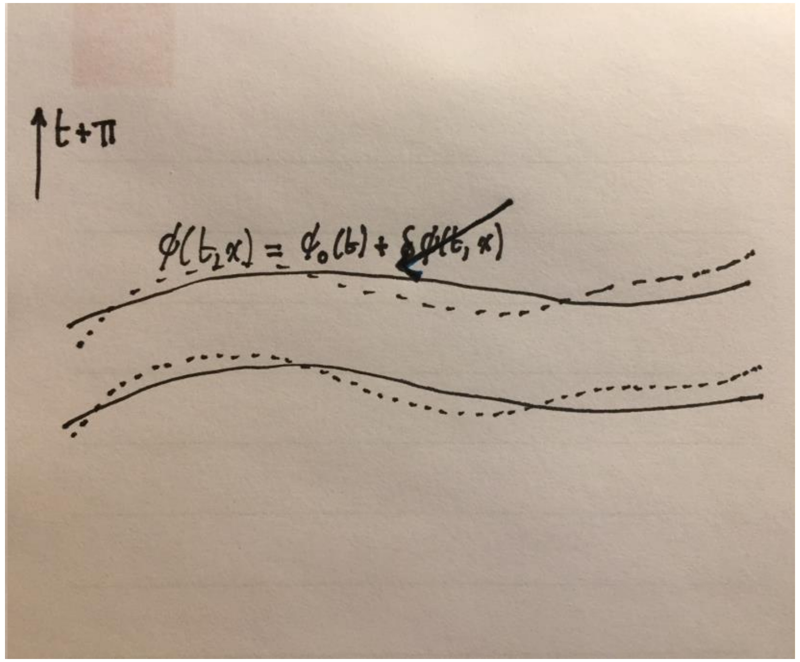
How do we relate this information to infer properties of an underlying effective theory?

Q) Where did the scalar perturbation go?



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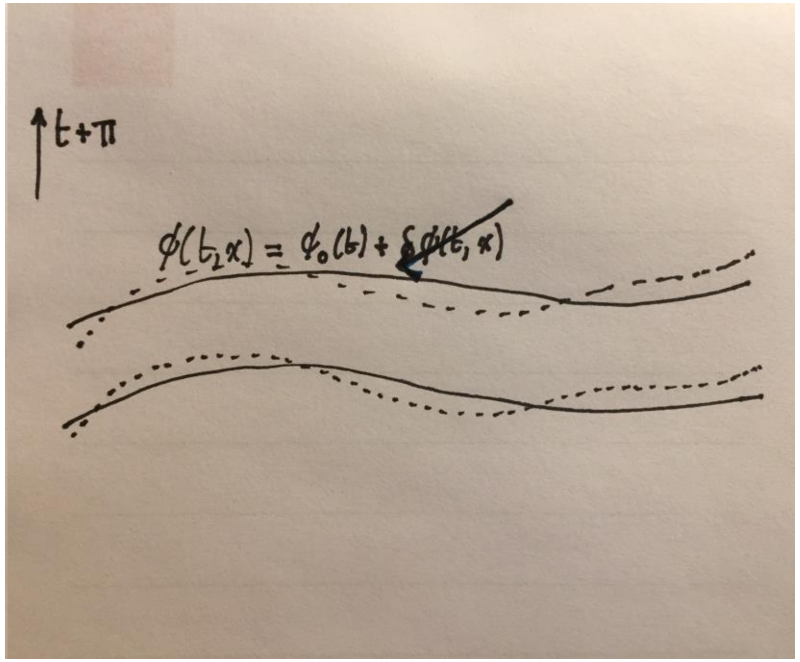
How do we relate this information to infer properties of an underlying effective theory?

A) It got `eaten' by the metric, which now propagates a longitudinal polarization…



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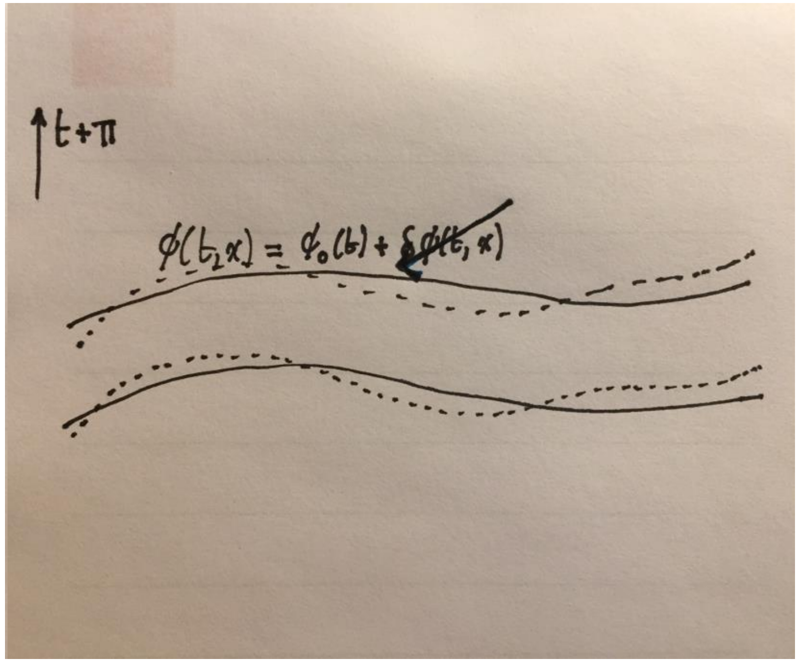
$$h_{ij} = a^2(t)e^{2\mathcal{R}}\delta_{ij}$$

Since $\mathcal{R}$ is a Goldstone, $\mathcal{R}$= const. will *always* be a solution for $k \ll 1$ to any order in perturbation theory since only derivative interactions. This is what imprints anisotropies on the CMB…



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$$h_{ij} = a^2(t)e^{2\mathcal{R}}\delta_{ij}$$

$$2\pi^2\delta^3(\vec{k}_1+\vec{k}_2)\mathcal{P}_{\mathcal{R}}(k_1) = k_1^3\langle\mathcal{R}(\vec{k}_1)\mathcal{R}(\vec{k}_2)\rangle$$

$$|\Psi\rangle = |0\rangle$$

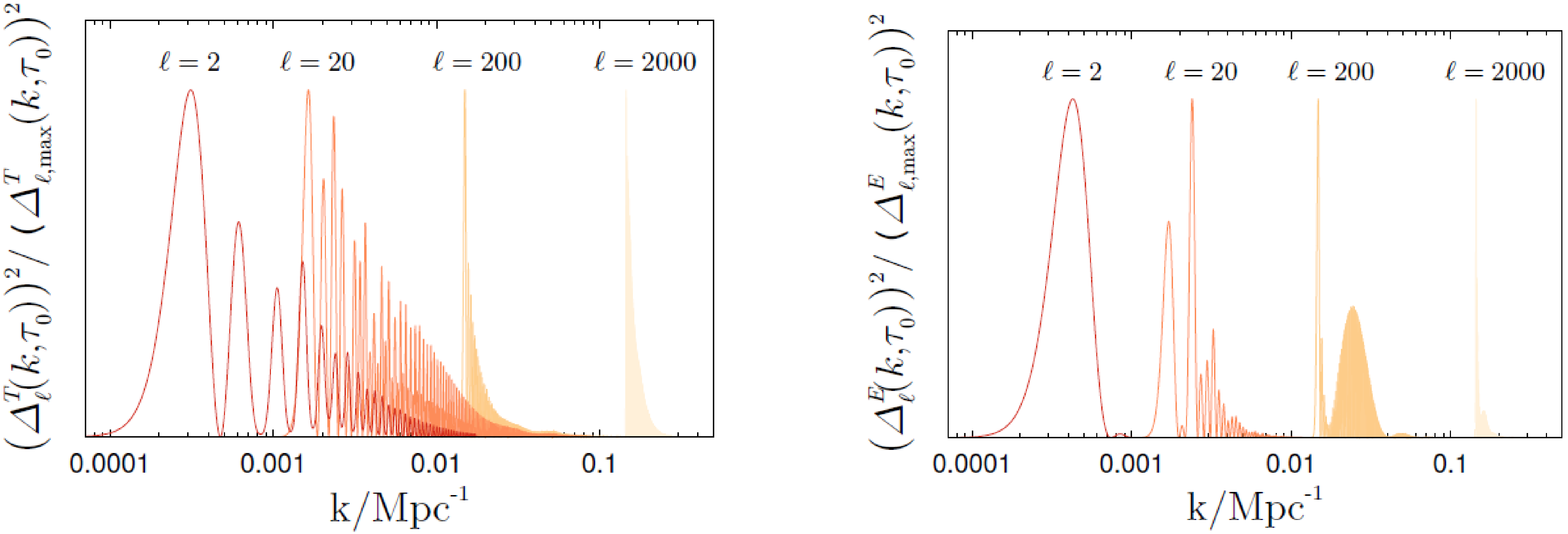
$$\frac{\Delta\widehat{T}}{\widehat{T}}(\vec{n}) = \sum_{\ell m} a_{\ell m}^T Y_{\ell m}(\vec{n})$$

$$\langle a_{\ell m}^X a_{\ell' m'}^{Y*}\rangle = C_\ell^{XY}\delta_{\ell\ell'}\delta_{mm'}$$

$$C_\ell^{XY} = \frac{1}{2\pi^2}\int \mathrm{d}\ln k\ \Delta_\ell^X(k,\tau_0)\Delta_\ell^Y(k,\tau_0)\mathcal{P}_{\mathcal{R}}(k)$$

$$\Delta_\ell^X(k,\tau_0) = \int_{\tau_{\rm ini}}^{\tau_0}\mathrm{d}\tau\ S^X(k,\tau)j_\ell(k(\tau-\tau_0))$$

non-primordial cosmology geometry



Are interesting things hiding in plain sight?

- All cosmological observations to date are consistent with adiabatic, Gaussian and nearly scale invariant initial conditions.

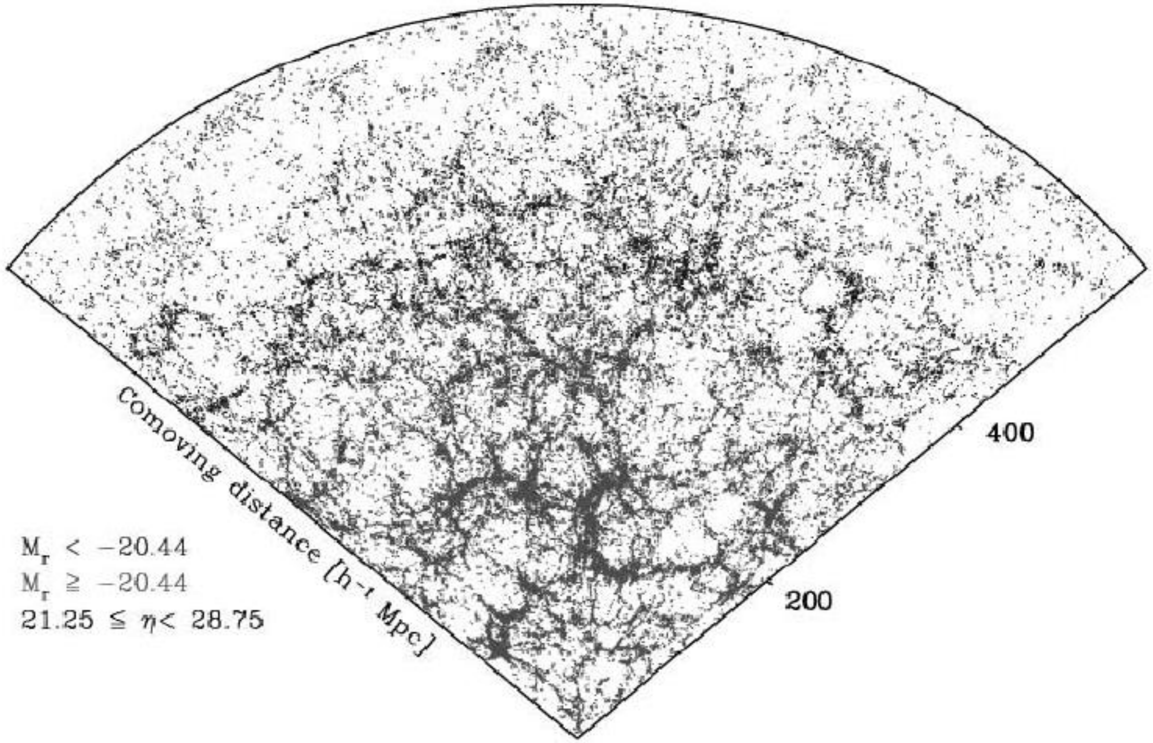
- Evidence of a particular symmetry breaking pattern in the very early universe (with a close to vanishing order parameter $\epsilon = -\dot{H}/H^2$).

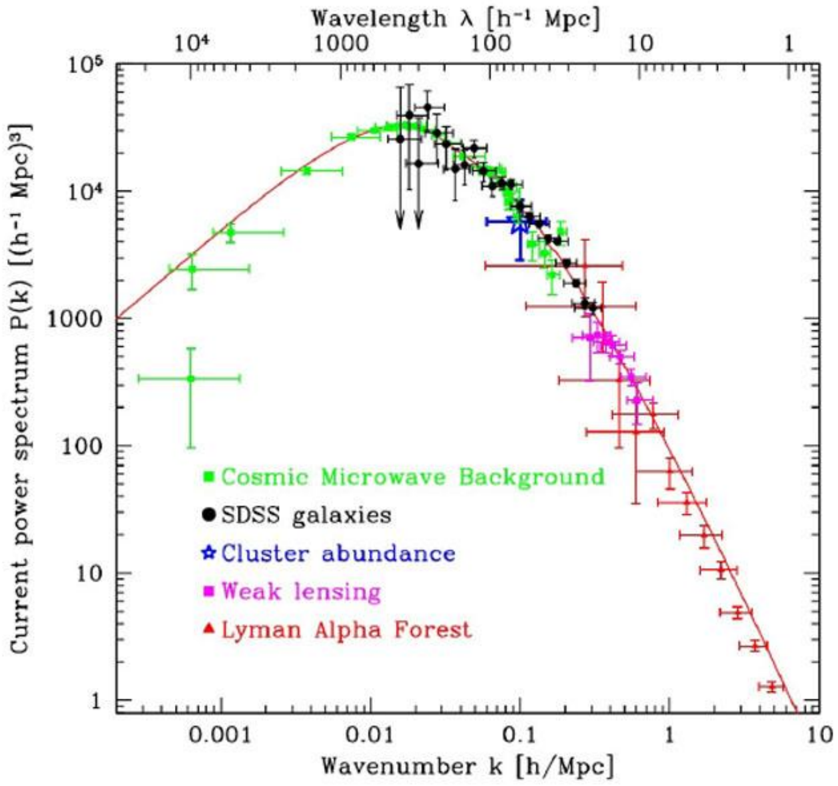
- Widely accepted as confirmation of the inflationary paradigm.

Large Scale Structure

$$\delta := \frac{\delta\rho}{\rho} \propto \nabla^2 \mathcal{R} \qquad \langle \delta(\vec{k}_1)\delta(\vec{k}_2)\rangle = (2\pi)^3 \delta(\vec{k}_1 + \vec{k}_2) P_m(k_1)$$

matter power spectrum





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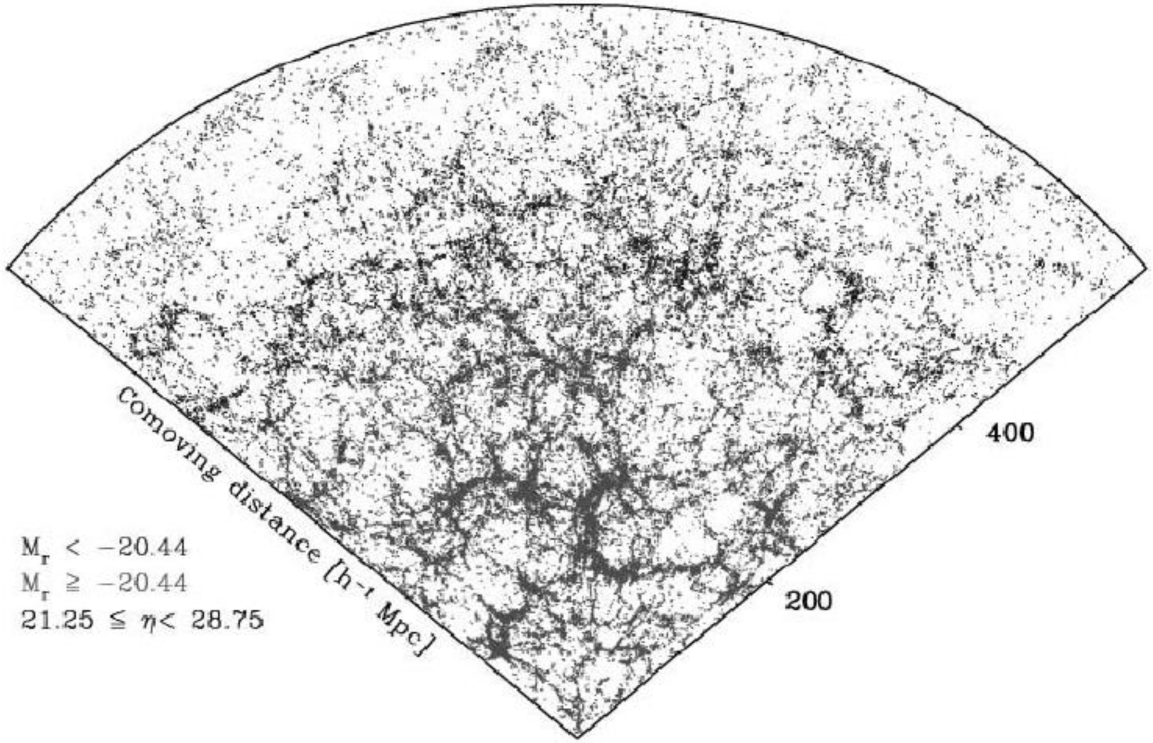
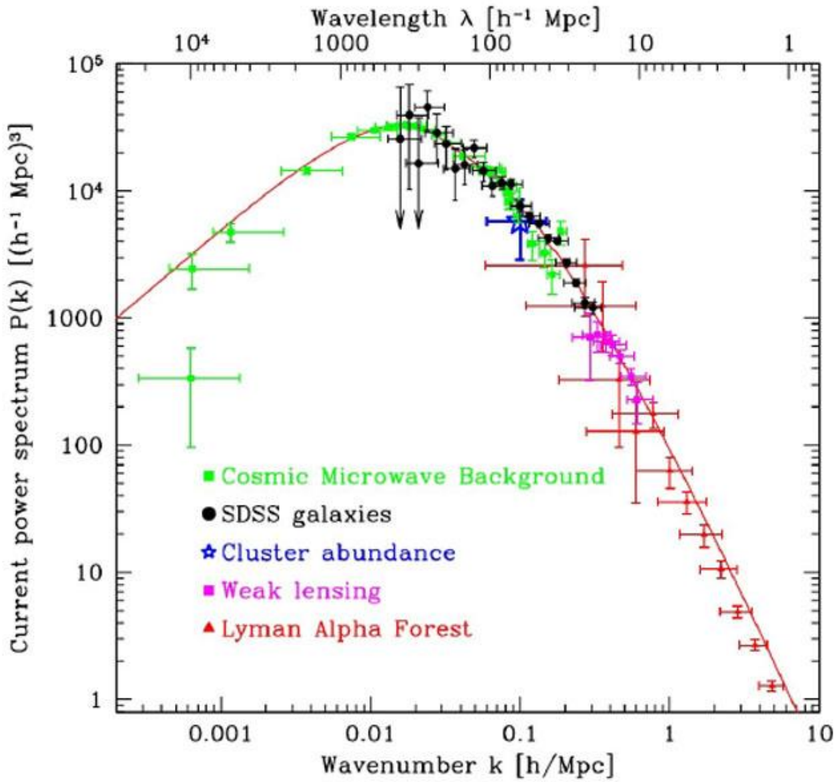
$\delta_{\rm galaxies} = f(\delta)$, linear bias $\rightarrow \delta_g = b(z)\delta$





This concludes the lightning tour, if you want more reading/ detailed references, ask me!