Cosmological opportunities for fundamental physics

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Outline

1. Introduction
2. Initial conditions for observable universe
   - What observations on CMB tell us
   - Problems with CMB
   - Possible solution?
3. Cosmological frontiers
4. Puzzles at the frontiers
5. Conclusions

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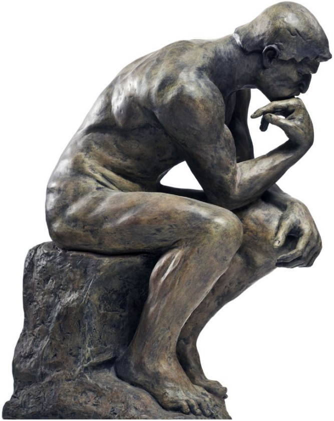
Precision cosmology is coming

A number of observation programs are ongoing and in plan

Precise data will be available soon

Observation-driven cosmology



Observations can lead to theoretical breakthrough

New cosmological passage for fundamental physics?

Exploit precise data to study cosmology and fundamental physics

1. What frontiers in cosmology shall we face?
2. What kind of information will we gain?

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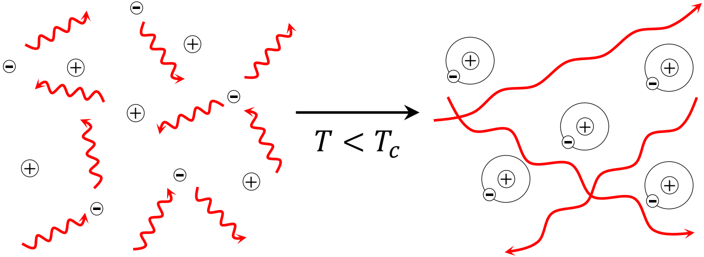
Cosmic microwave background (CMB)

- First observed by chance in 1965
- Extremely homogeneous and isotropic
- $T_0 = 2.725$ K, corresponding to $\lambda \approx 0.075$ m (microwave)

How is CMB generated?

- The early universe contained free electron + proton + photon
- As the universe expands so $T < T_c$, neutral hydrogens formed
- No free electrons to scatter off, photons can propagate straight



Characters of CMB

- Earliest universe observable by photons (EM waves)
- Perfect blackbody spectrum due to thermal equilibrium
- Homogeneous and isotropic

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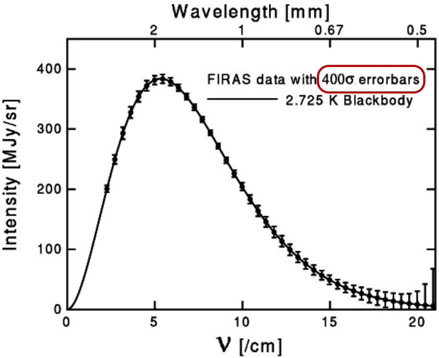

Most perfect blackbody spectrum ever observed

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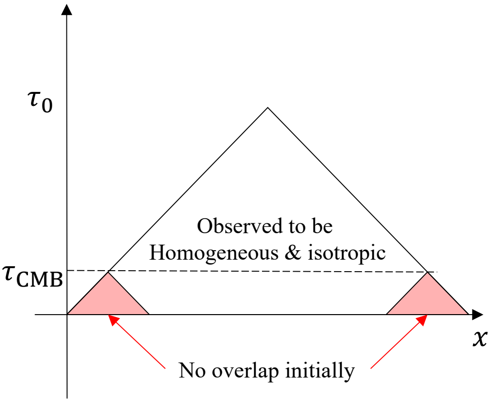
Homogeneity beyond causal communication

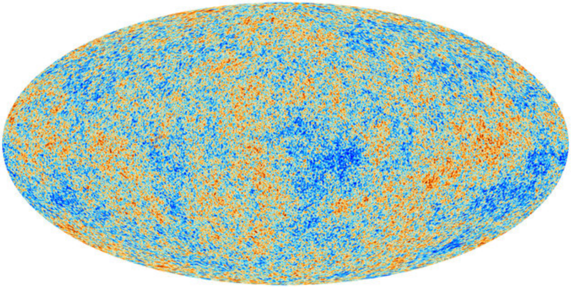
After big bang photons cannot travel a distance encompassing CMB



“Horizon problem”

Temperature fluctuations of CMB

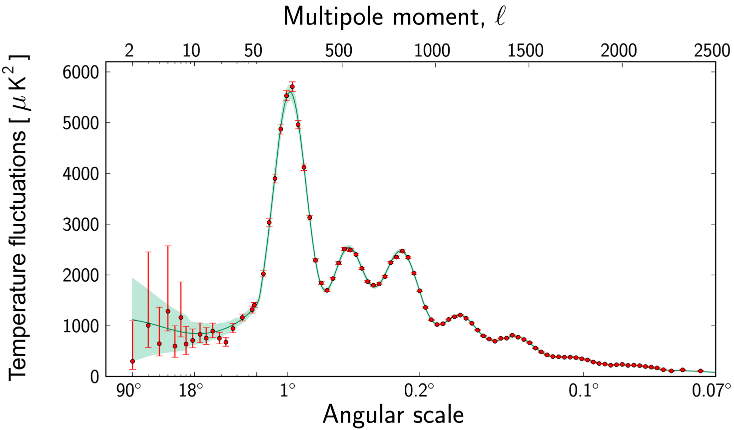
Homogeneity is not the only problem of the CMB...



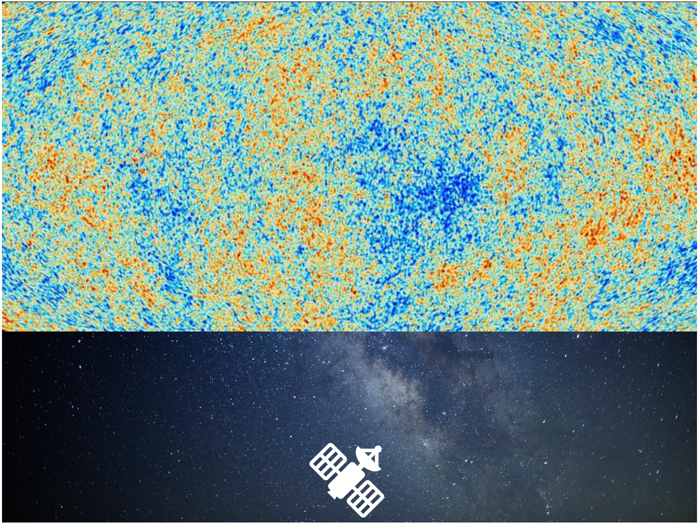
High resolution reveals genuine temperature fluctuation of $\mathcal{O}(10^{-5})$

CMB power spectrum

This is the famous CMB spectrum you must have seen many times



How is the CMB power spectrum obtained?



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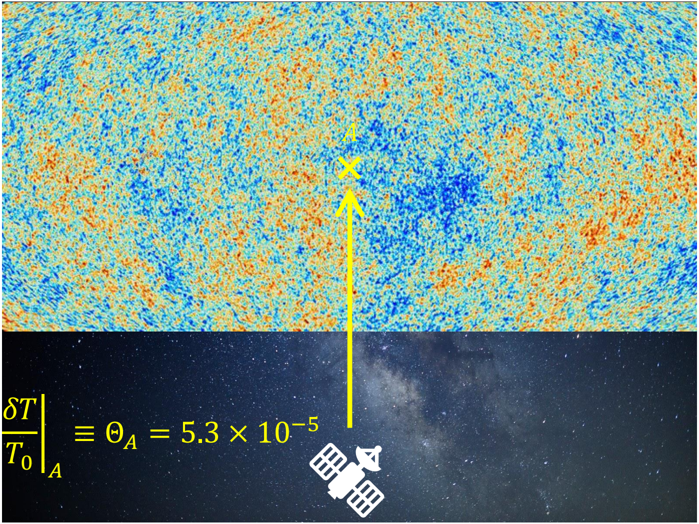

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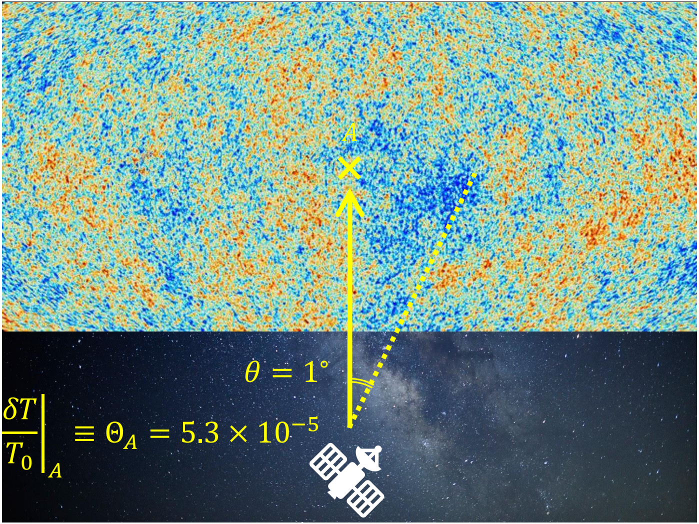

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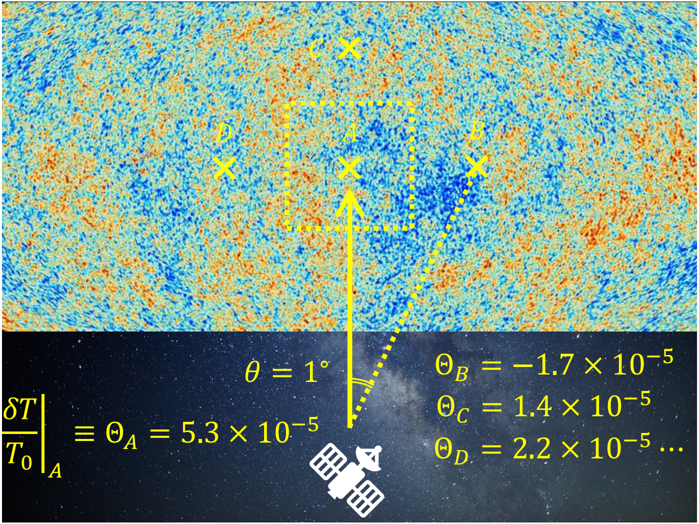

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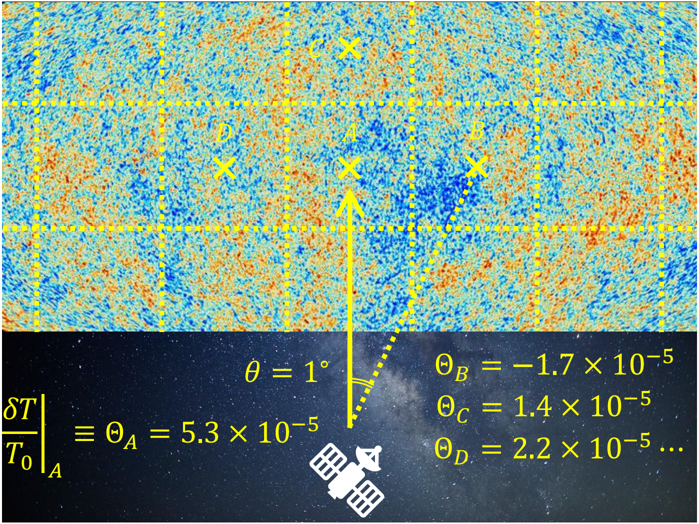

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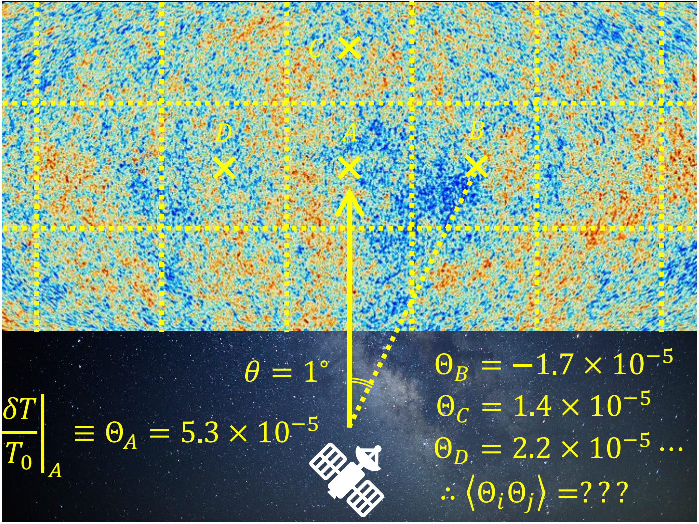


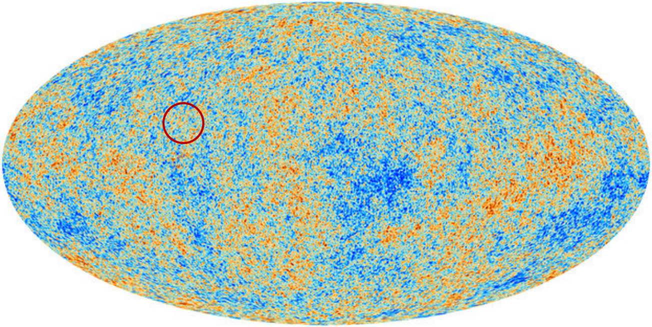
How is the CMB power spectrum obtained?

Decomposing $\delta T/T_0$ using $Y_{\ell m}(\hat{\boldsymbol{n}})$ gives CMB power spectrum

$$\frac{\delta T(\hat{\boldsymbol{n}})}{T_0} = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{\boldsymbol{n}}) \quad \to \quad C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

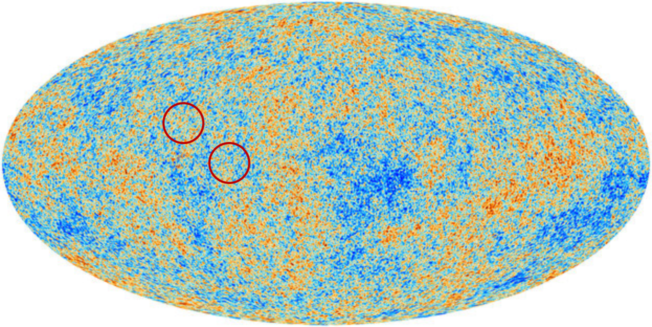
Correlation beyond causal patch

- Size of causal patch ≈ size of full moon (1°) (circle exaggerated)



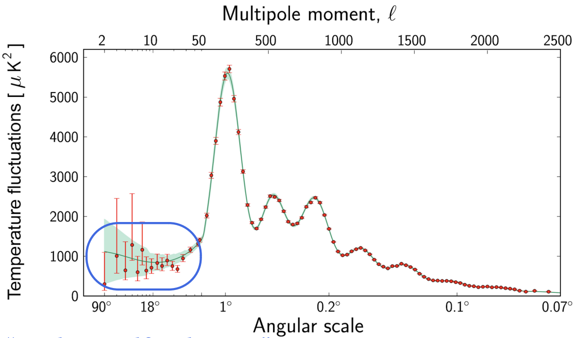
Correlation beyond causal patch

- Size of causal patch ≈ size of full moon (1°) (circle exaggerated)
- Correlations between 2 points separated larger than 1°?



Correlation beyond causal patch

- Size of causal patch ≈ size of full moon (1°) (circle exaggerated)
- Correlations between 2 points separated larger than 1°?
- Non-vanishing correlations with nearly constant amplitude



"Sachs-Wolfe plateau"

Puzzles to be addressed

- Therefore we need to explain, at the same time, the following:
  1. Extremely homogeneous and isotropic universe
  2. Origin of temperature fluctuations
  3. Non-vanishing correlation beyond causality
- Such initial conditions at $t_{\rm Pl}$ need fine tuning of $\mathcal{O}(10^{-60})$
- This is very very very disturbing...

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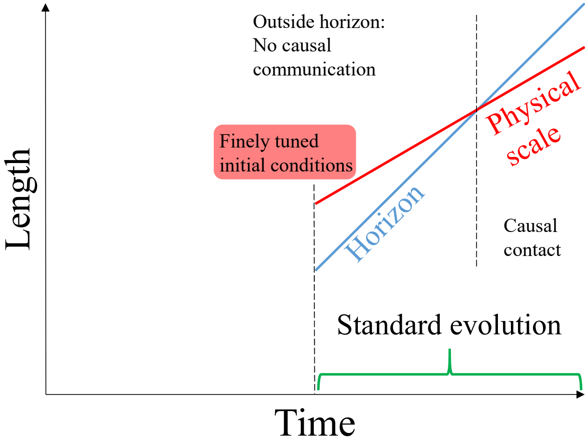
What is inflation?

Inflation = accelerated expansion before hot big bang evolution



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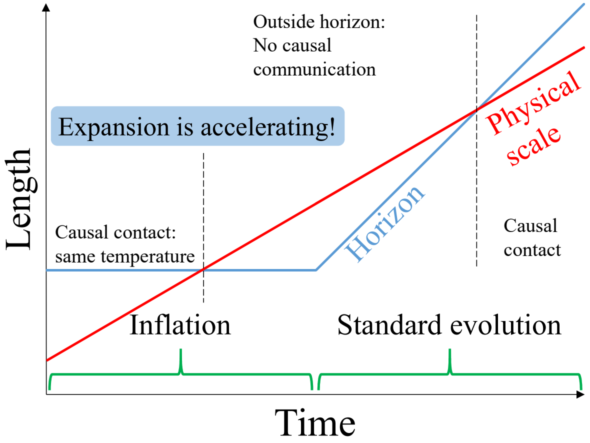

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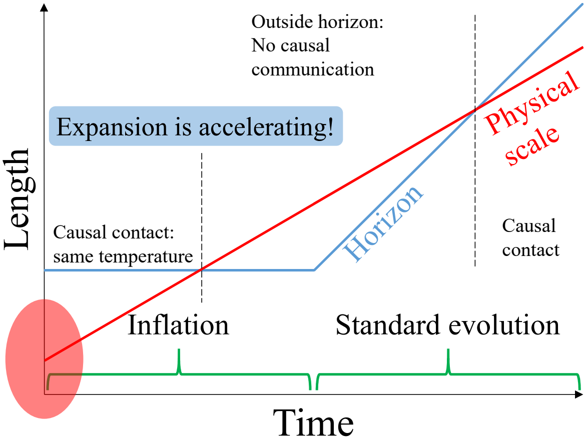
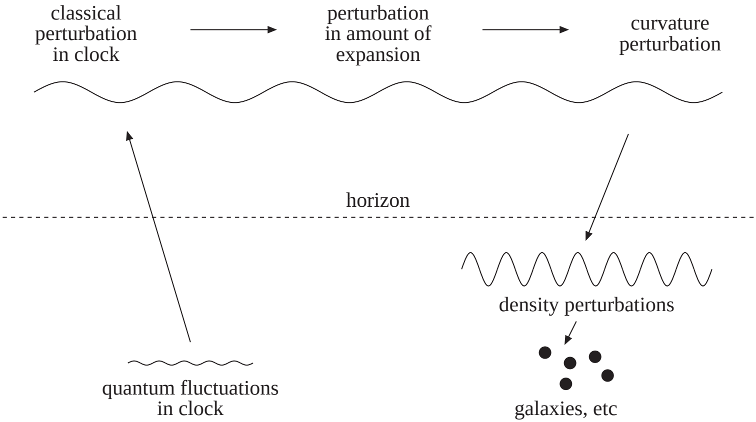


Quantum mechanics is relevant during inflation

Generation and evolution of perturbations



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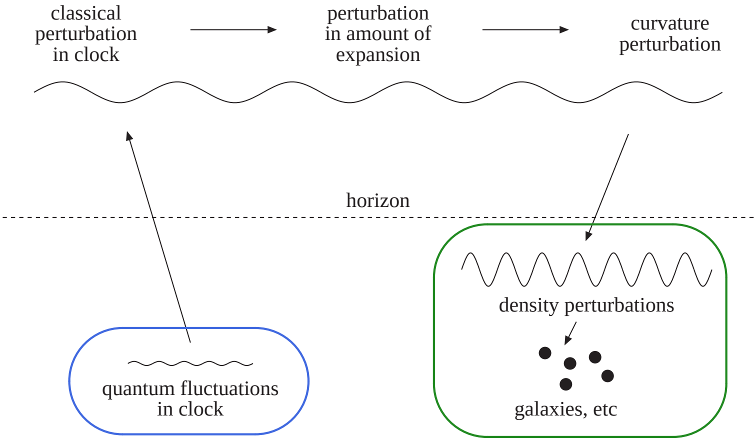

QM signatures on cosmic scales, e.g. $\delta T/T_0$ of CMB

Scalar and tensor perturbations

Distance between 2 points in space

$$dl^2 = a^2(t)\left\{[1+2\mathscr{R}(t,\boldsymbol{x})]\delta_{ij} + h_{ij}(t,\boldsymbol{x})\right]dx^i dx^j$$

2 geometric perturbations constrained by observations

- $\mathscr{R}(t,\boldsymbol{x})$: Curvature perturbation (scalar)
- $h_{ij}(t,\boldsymbol{x})$: Gravitational waves (tensor)

We treat these perturbations quantum mechanically

Observation-driven cosmology (reprise)

Close observations on CMB and cosmic structure gives us hints on

1. Physical laws on extremely high energy scales
2. Interactions relevant on such energies

These energies are far higher than any terrestrial accelerators

Cosmology provides unique opportunity to study fundamental physics

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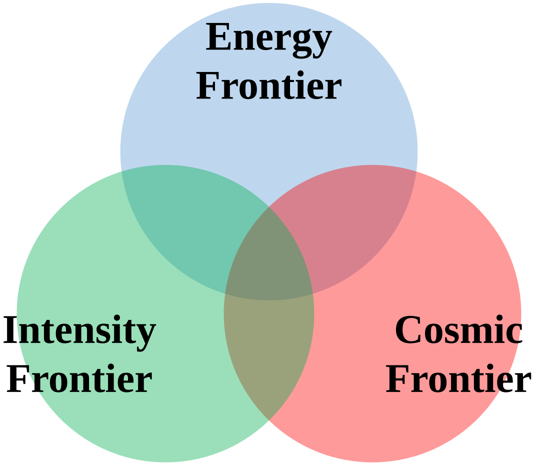
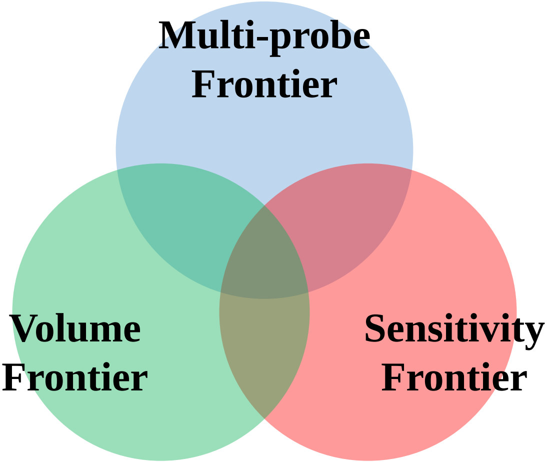
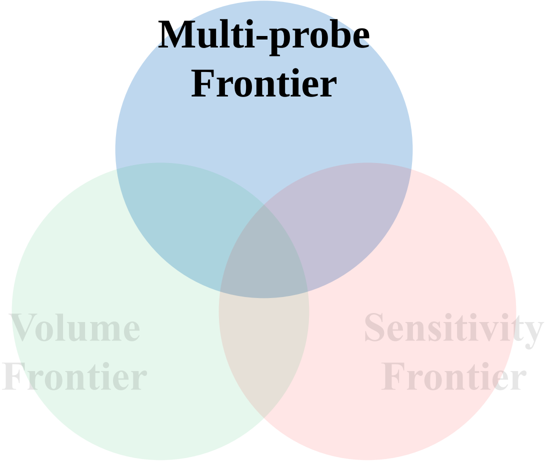
Frontiers for particle physics



… then frontiers for cosmology?



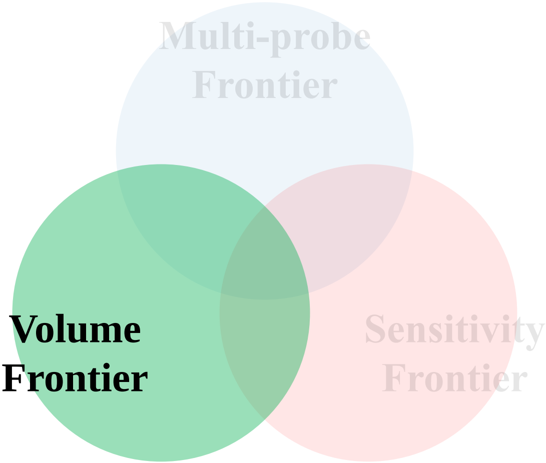
Multi-probe frontier



Multi-probe frontier

- Multi-messenger
  - Gravitational waves, neutrinos...
  - Different “eyes” to look into the universe
  - Advanced LIGO, eLISA, LiteBIRD, TianQin, DECIGO, KAGRA, IceCUBE, DUNE, Hyper-Kamiokande...
- Multi-wavelength
  - Complementary map by radio telescopes, near-IR observations
  - Square Kilometer Array, Tianlai, SPHEREx...
  - New large-area radio data (HI intensity mapping, HI galaxies, radio WL shear...)

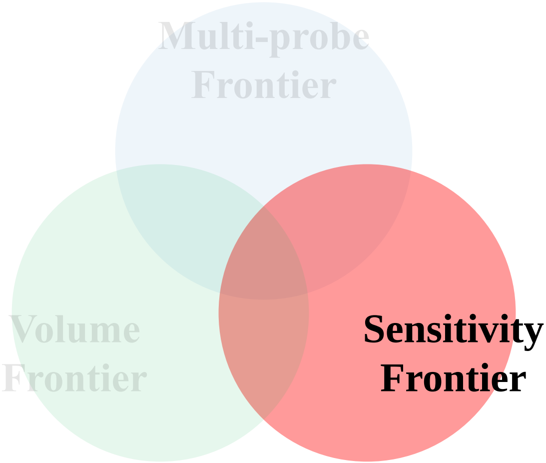
Volume frontier



Volume frontier

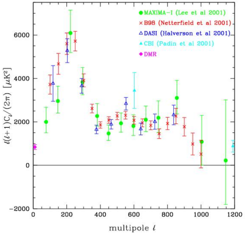
- Large-scale surveys with multiple timeframe
  [DESI (2019-), LSST (2022-), Euclid (2023-), WFIRST (mid 20)...]
- Huge advance in survey volume
  - 90s (2dFGRS): $\mathcal{O}(50,000)$ galaxies up to $z \sim 0.2$ - 0.3
  - Planned (Euclid): 10 billion galaxies with mid redshift 0.7 - 0.9 (max $z \sim 3$)
- The larger the survey volume is, the more data we will gain

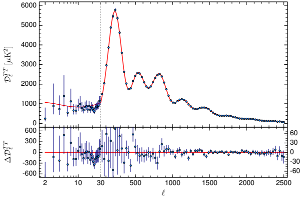
Sensitivity frontier



Sensitivity frontier

- Advances in instrument technologies, e.g. CMB (90s vs 2010s)





- Parameters beyond ΛCDM to be further constrained/detected (e.g. running of $n_{\mathcal{R}}$, primordial GWs, non-Gaussianity...)
- ΛCDM parameters in poorly explored regime to be constrained (e.g. CMB μ/y-distorsion $\to \mathscr{P}_{\mathcal{R}}$ on small-scales)

New discoveries to come

Cosmological frontier will work together

1. with new detections / stronger constraints
2. with multiple frequencies and messengers
3. with significantly better confidence

Then what puzzles lie ahead?

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Puzzle 1: Which messengers are there?

- We have cosmic background of GWs and νs, but what else?
- Several requirements for such messengers with background:
  1. (Until recently) relativistic
  2. Weak but strong enough interactions
- Any BSM may contain many candidates, e.g. dark photons
- But should not be too arbitrary – well motivated!

What messenger can you think of with physical importance?

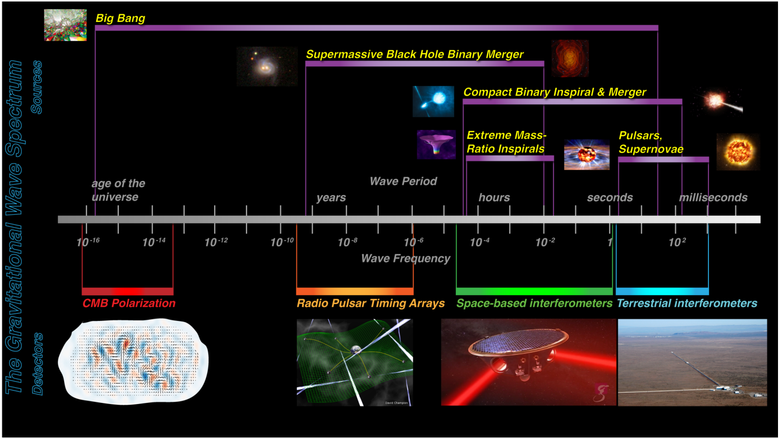
Puzzle 1': Which messengers are there?

- Cosmic background is not the only possibility
- Stellar objects could be "factory" for new messengers
  1. Stellar ignition could be accelerated / decelerated by DM
  2. SN / neutron stars may emit strong jets of new particles
  3. Accretion discs around BHs may well emit energetic particles

How do new particles intervene SM interactions?

Puzzle 2: How to detect them?

Consider the background of GWs as an example



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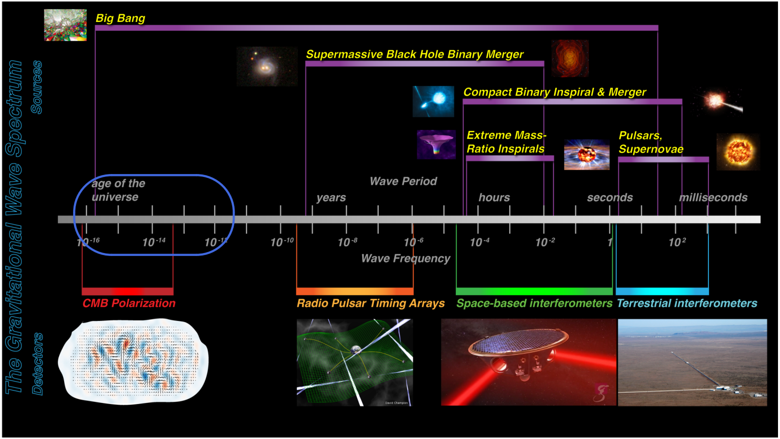
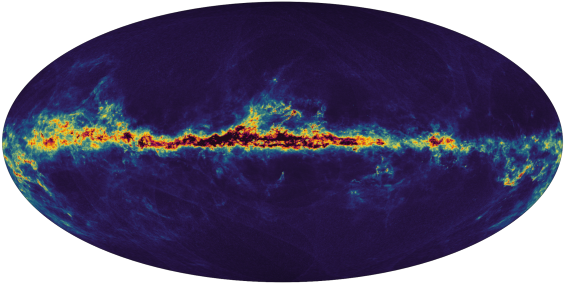


How to detect ultra-low frequency GWs?

Puzzle 3: How to understand small-scale effects?

- Intergalactic dust is important but not well understood

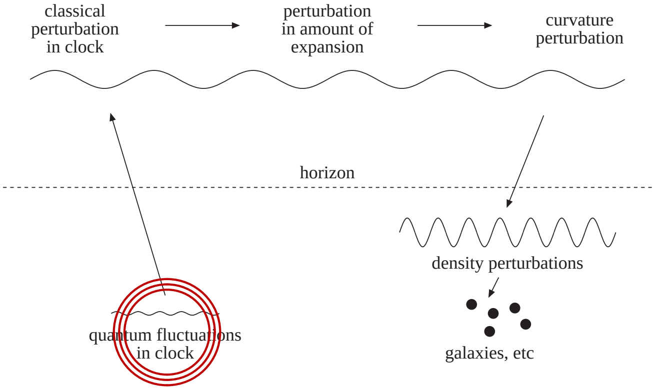


- Similarly for dark matter haloes, weak lensing...

Can we construct concrete theoretical models?

Puzzle 4: Any quantum effects on cosmological scales?

Cosmic structure is classical, even if originated from QM effects



How to test quantum origin of cosmic structure?

Puzzle 5: How to reduce systematics/variance?

- Data is a huge collection of set of numbers
- How to sample them leads to different statistical measure
  Example: Galaxy survey data → 2-pt fct in real / Fourier space
- Correlating different tracers could help (e.g. cluster-void)

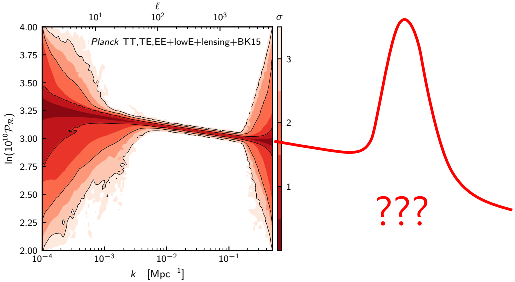
Clever statistical / mathematical approach?

Puzzle 6: New parametrization of observables?

- Consider the scalar primordial power spectrum as an example:

$$\mathscr{P}_{\mathscr{R}}(k) = A_{\mathscr{R}}\left(\frac{k}{k_0}\right)^{n_{\mathscr{R}}-1+\frac{1}{2}\alpha_{\mathscr{R}}\log\left(\frac{k}{k_0}\right)+\cdots} \quad \begin{cases} A_{\mathscr{R}} &= 2.0968^{+0.0296}_{-0.0292}\times 10^{-9} \\ n_{\mathscr{R}} &= 0.9652\pm 0.0042 \\ \alpha_{\mathscr{R}} &= -0.0041\pm 0.0067 \ (68\%) \end{cases}$$

- No guarantee for validity all the way (e.g. PBH formation)



Data-driven / non-parametric reconstruction?

Puzzle 7: Do we live in a typical universe or not?

- We run numerical simulation many times to obtain mock data
- In reality, we observe only 1 universe
- From theoretical viewpoint, our universe may (not) be typical (landscape - swampland in string theory, eternal inflation...)

How can we test the typicality of our universe?

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Conclusions

- Cosmology in the era of precision observations
- Unique opportunity to study fundamental physics
- Cosmological frontiers
  1. Multi-probe frontier: new eyes and windows into the universe
  2. Volume frontier: mapping the universe as huge as possible
  3. Sensitivity frontier: quest for unconstrained parameters
- We need theoretically well-posed idea, bringing more questions to be answered