Cosmology

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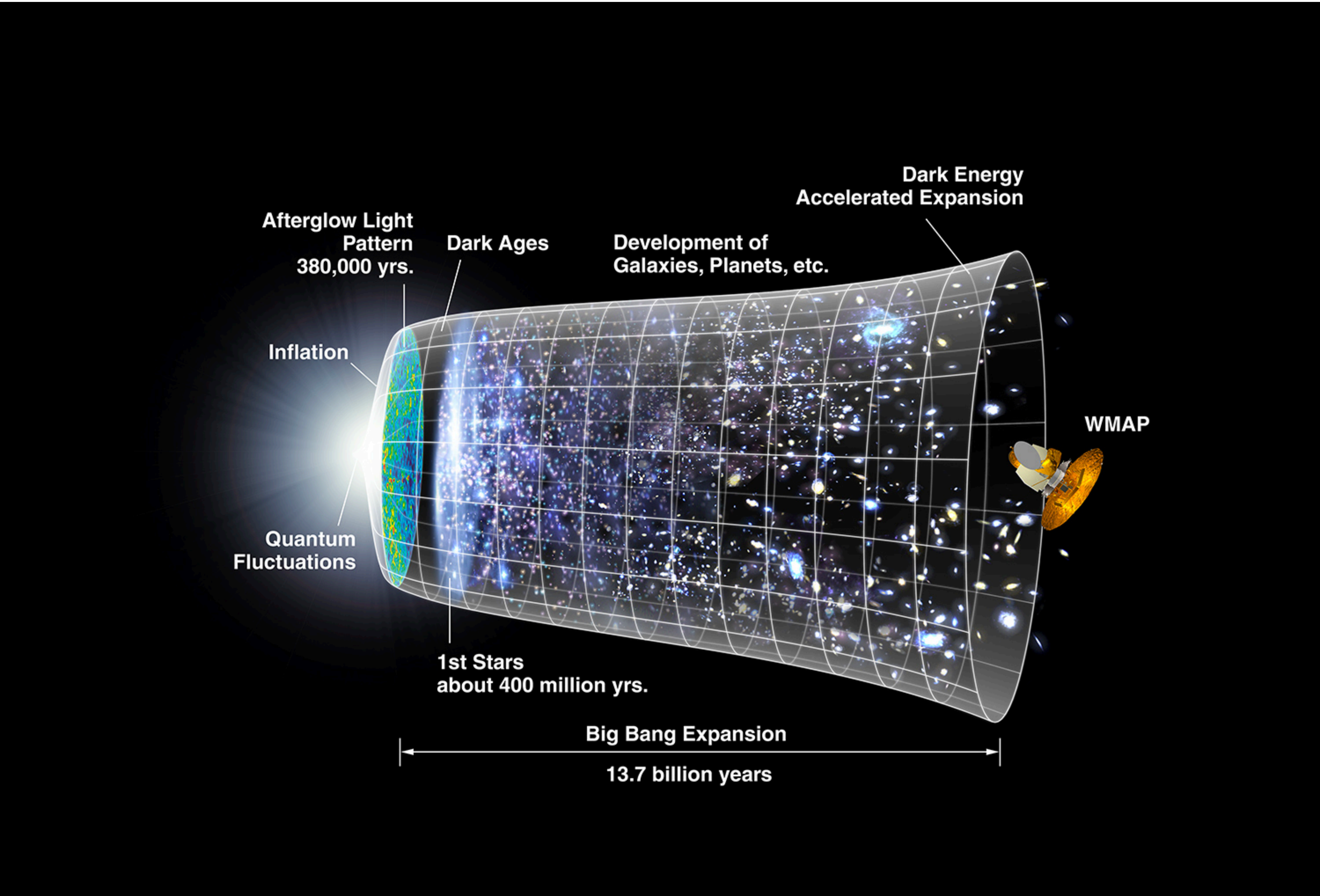
Journée P2I PHOM - Orme des merisiers

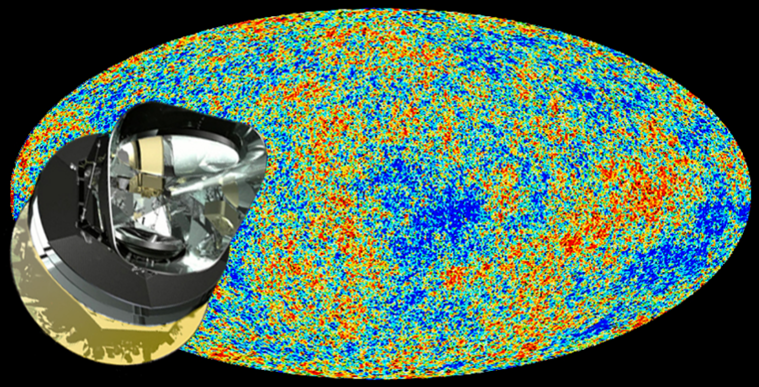
Standard cosmological model



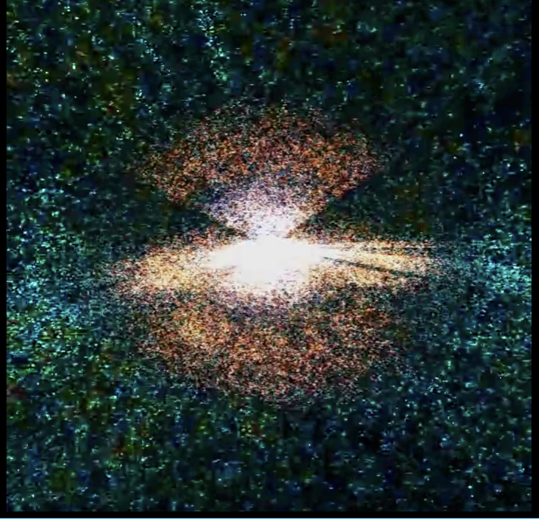
Scientific context

Rich present and future observational context…

WMAP, Planck, …

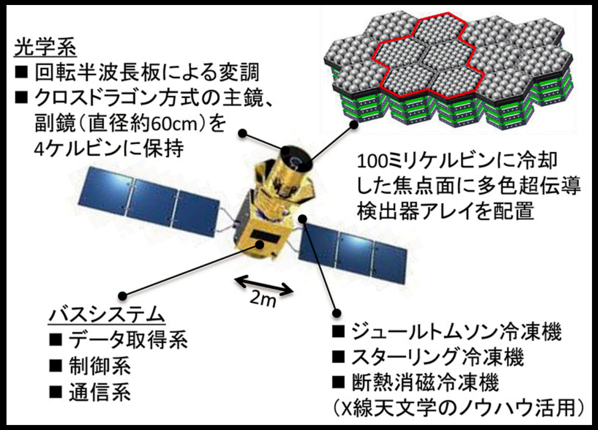


SDSS, DES, …

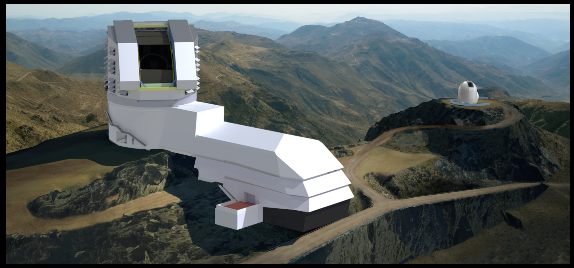


LIGO/Virgo

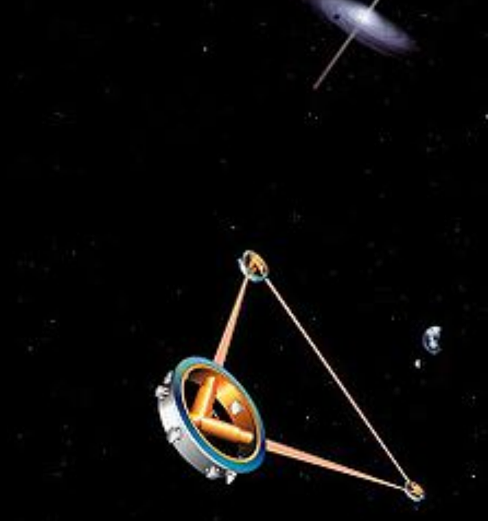
Polarisation du CMB



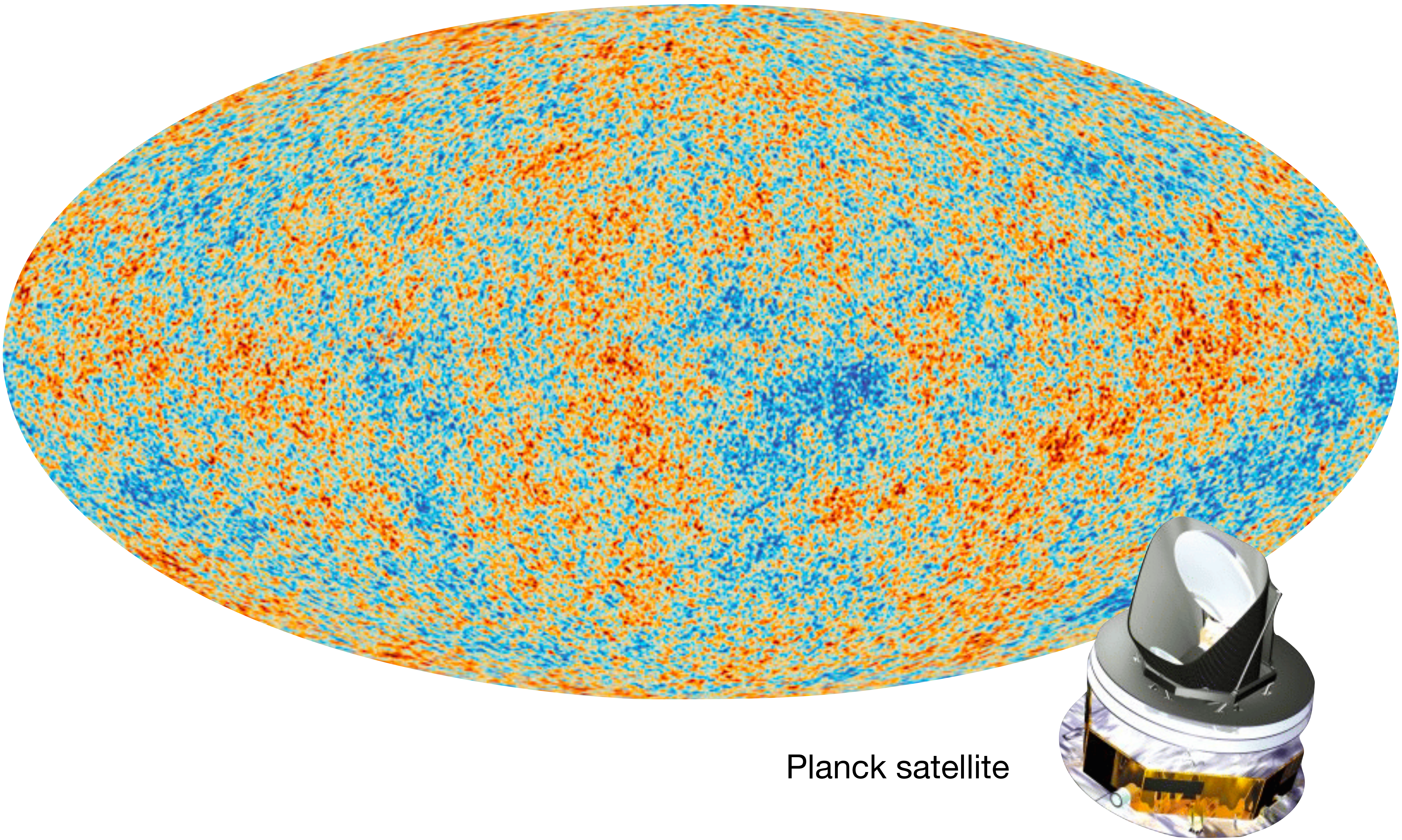
Euclid, LSST 2022



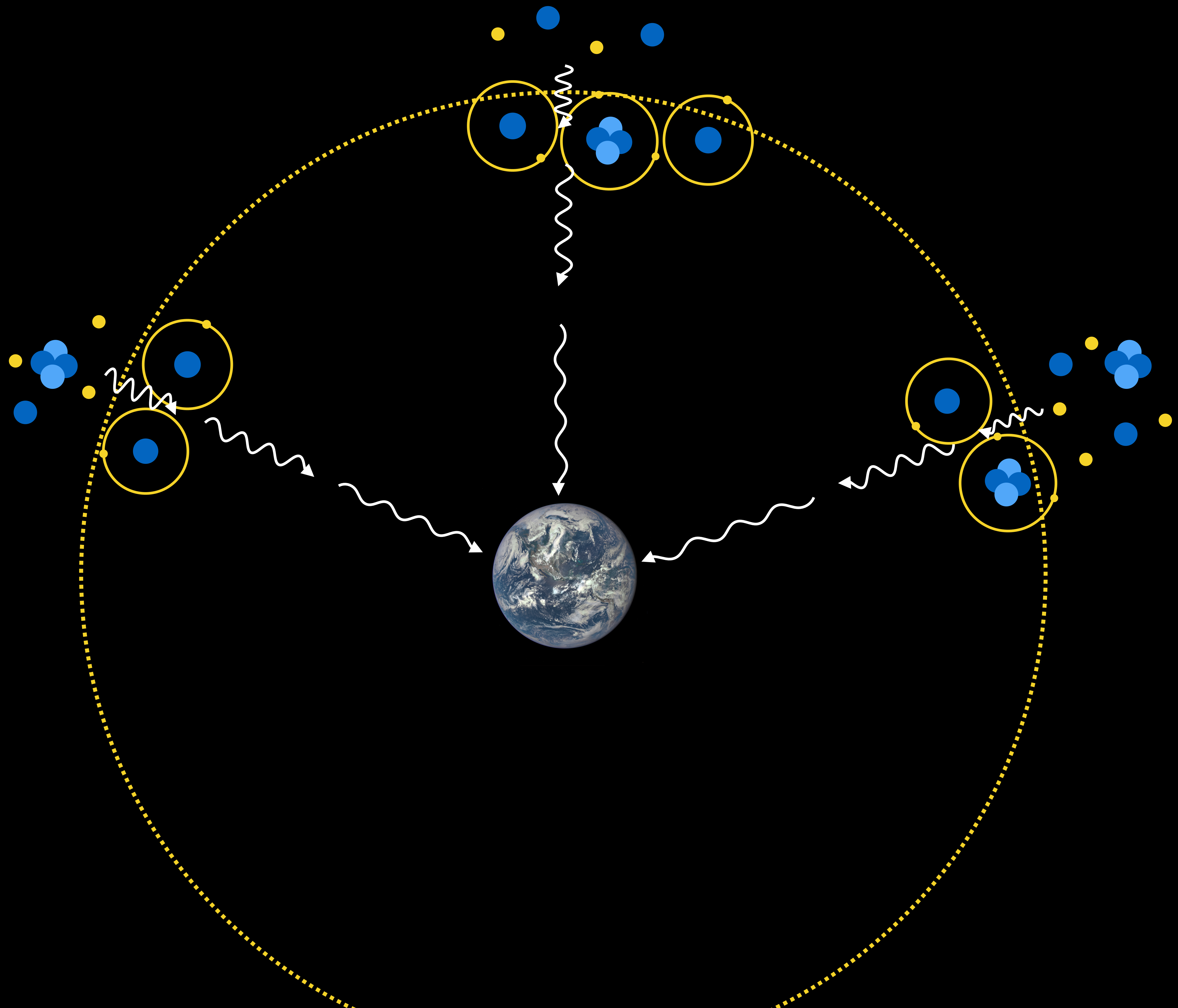
LISA 2034



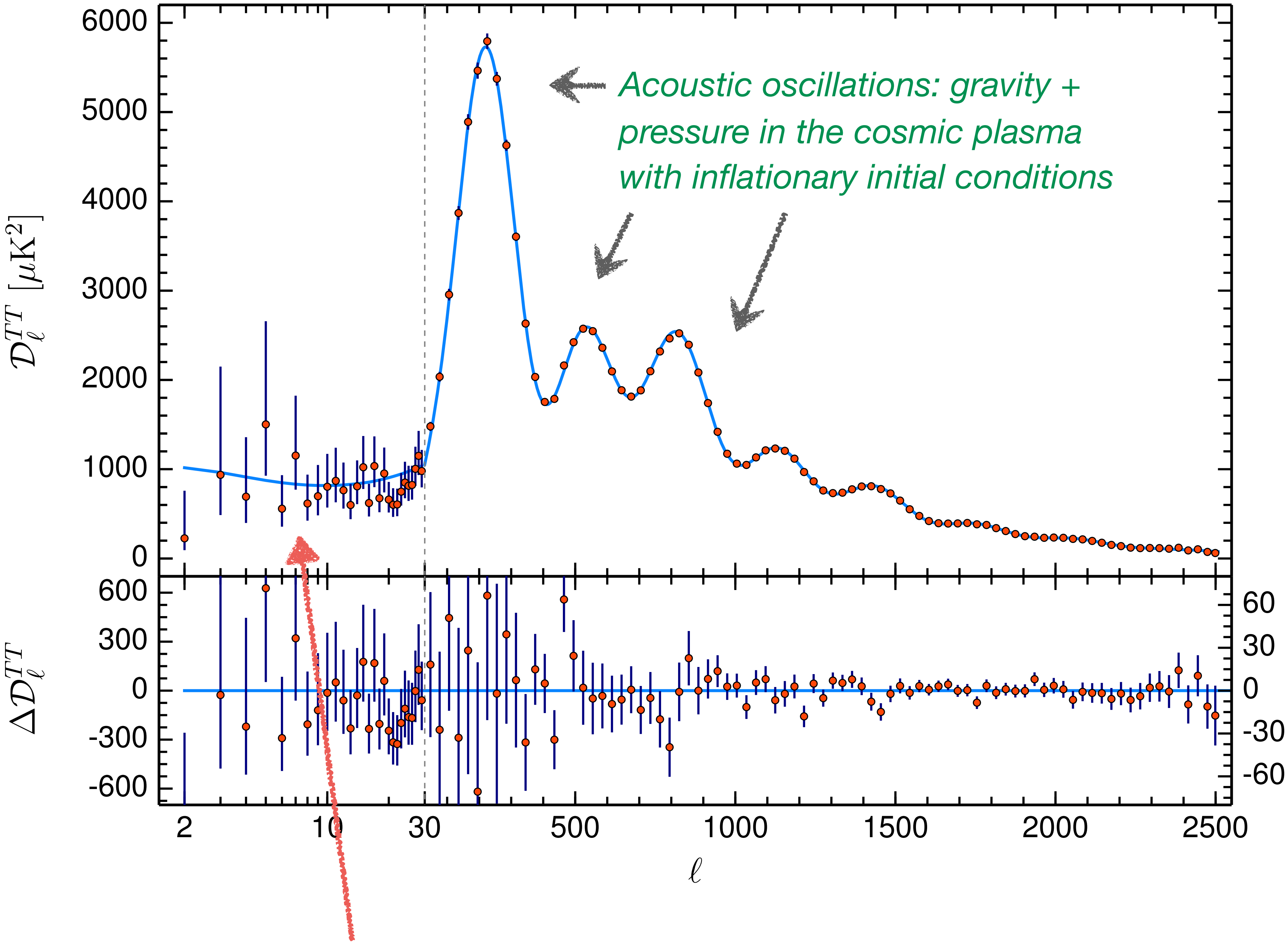
Cosmic Microwave Background: Temperature



Planck satellite

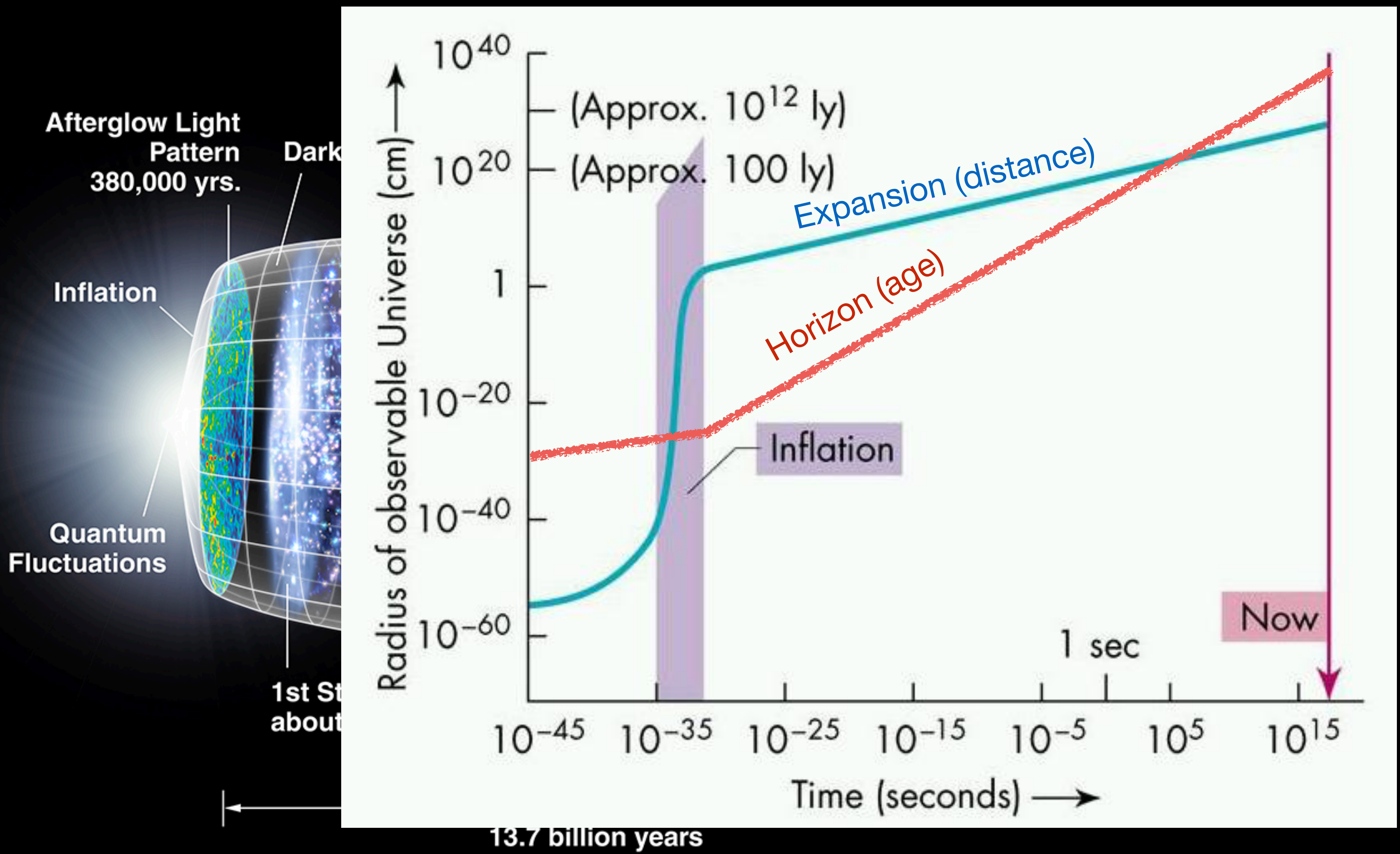


Primordial correlations: Temperature



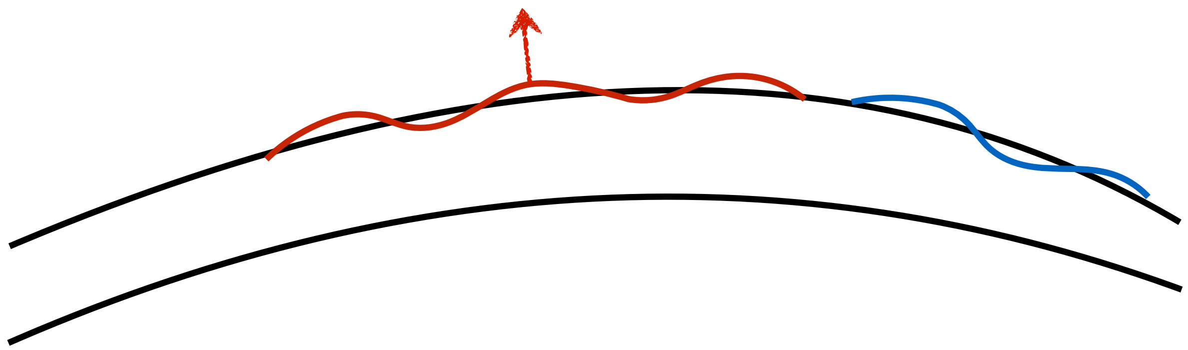
Fluctuations created before the hot Big Bang

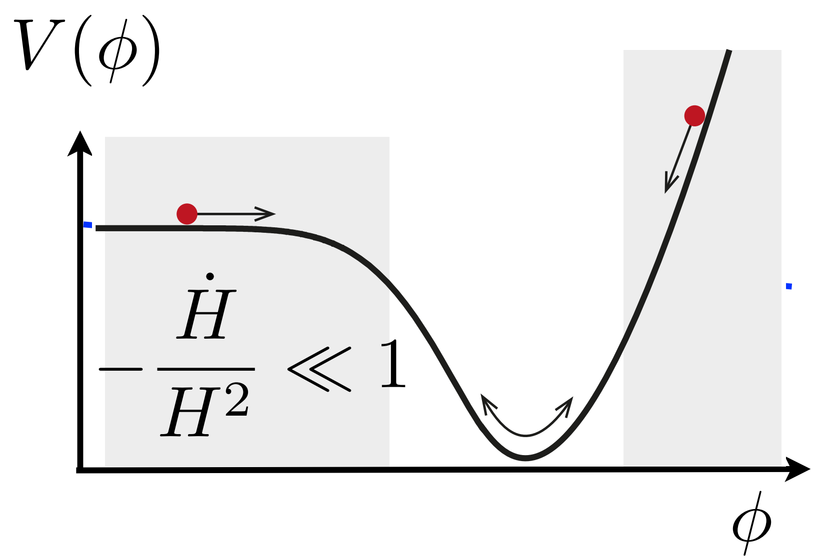
Cosmic inflation



Quantum fluctuations

Inflation is dominated by a scalar field





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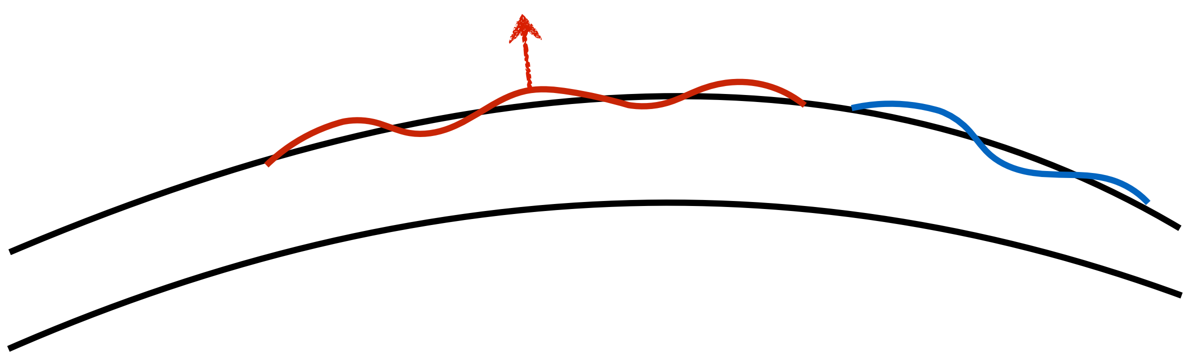
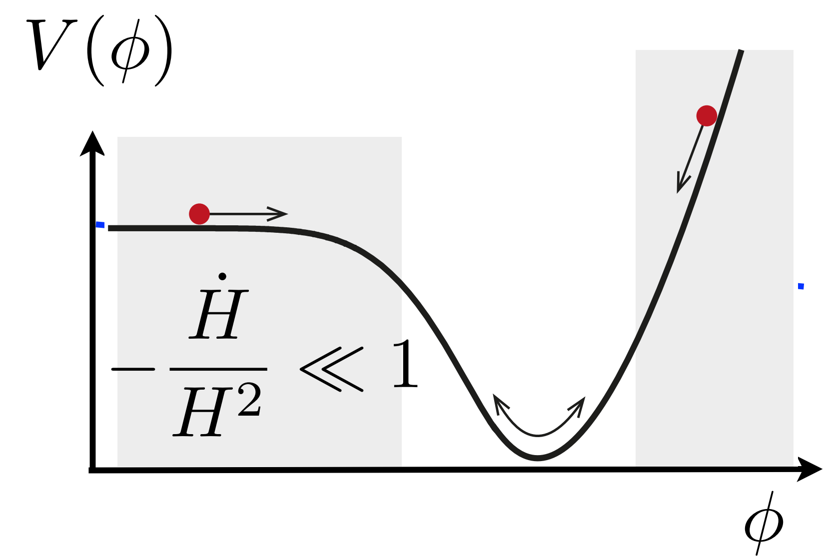
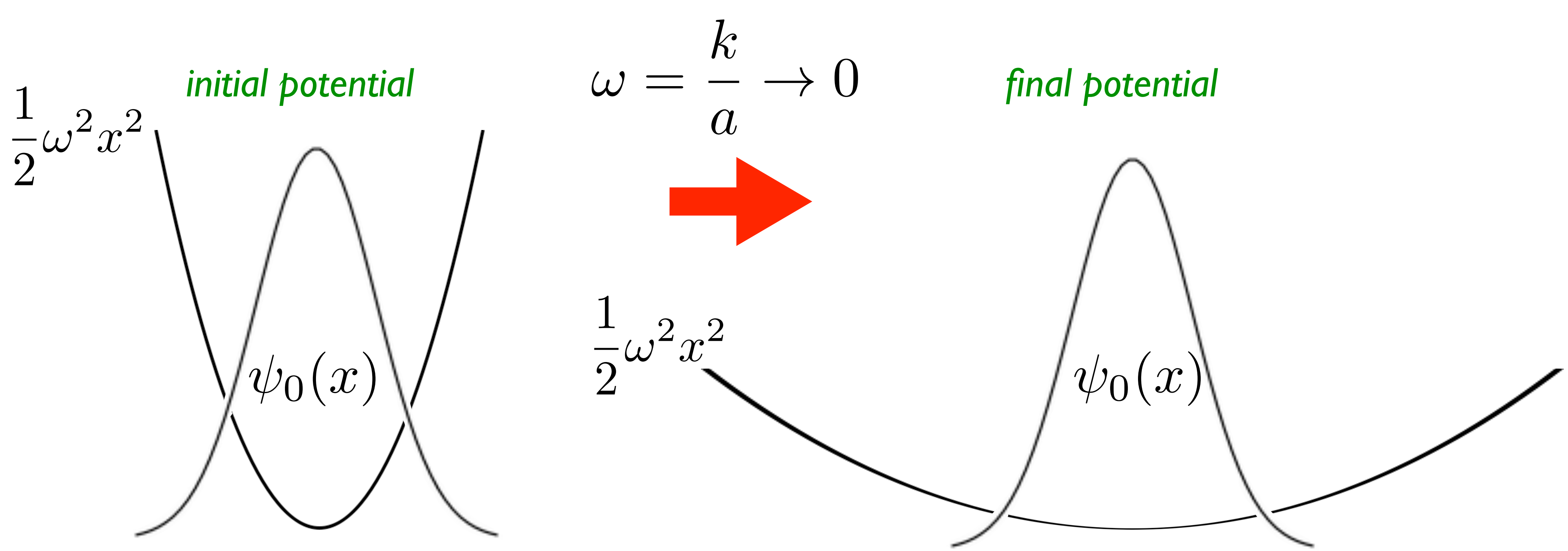




Scalar field has perturbations around homogeneous background. Each Fourier mode is a quantum harmonic oscillator with time dependent spring "constant"



$\omega \gg H$ • High frequency: vacuum I.C.

$\omega \ll H$ • Low frequency: fluctuations freeze-in

Primordial perturbations from inflation

Two types of perturbations are guaranteed to be created from inflation:

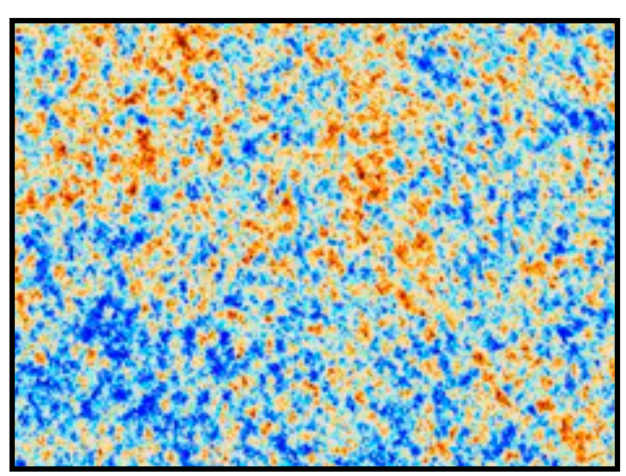
$$g_{ij} = e^{2Ht}\left[(1+\zeta)\delta_{ij} + \gamma_{ij}\right]$$

expansion
(accelerated expansion)

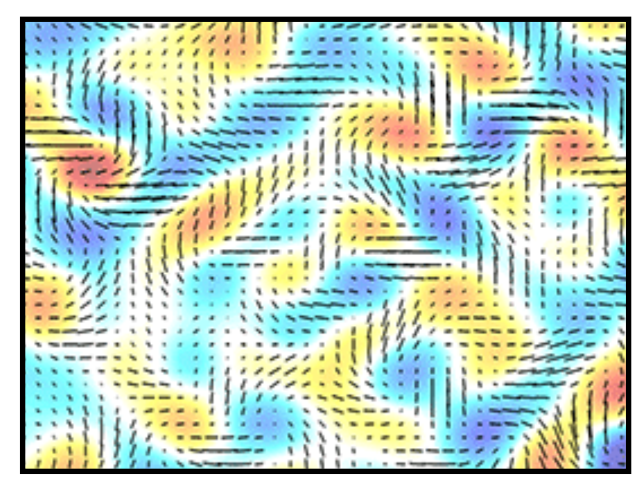
scalar perts.
(isotropic stretching)

tensor (GW) perts.
(anisotropic stretching)

Temperature (scalar)



B-mode polarization (tensor)



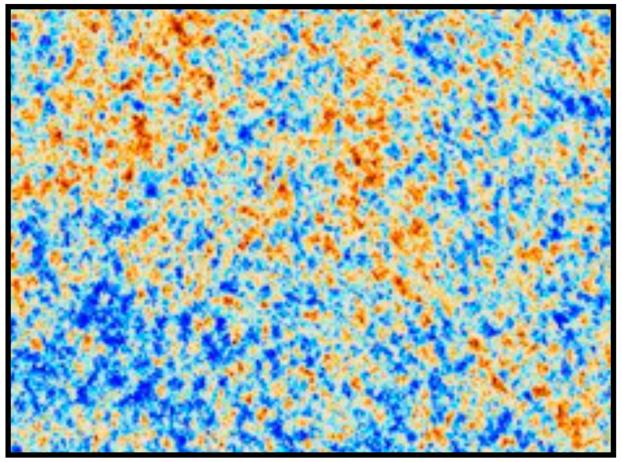
Open questions

Extraordinary claims need extraordinary evidence

- Did inflation really occur?
- What is its physical mechanism? (How many fields, which interactions…)
- What is the energy scale?
- How did it begin/end?
- …

Opportunity to learn new fundamental physics from future observations

Temperature (scalar)



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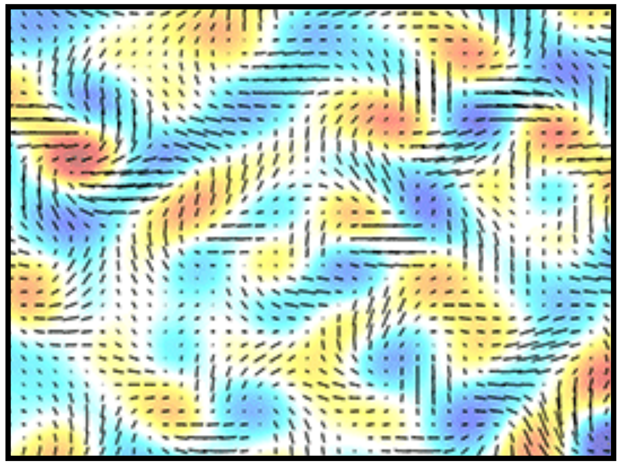

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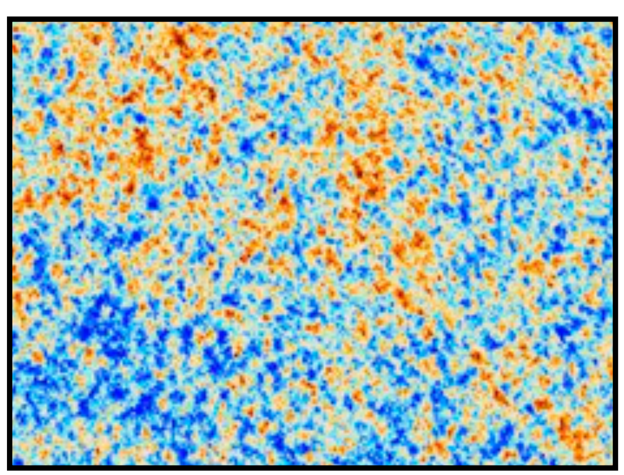

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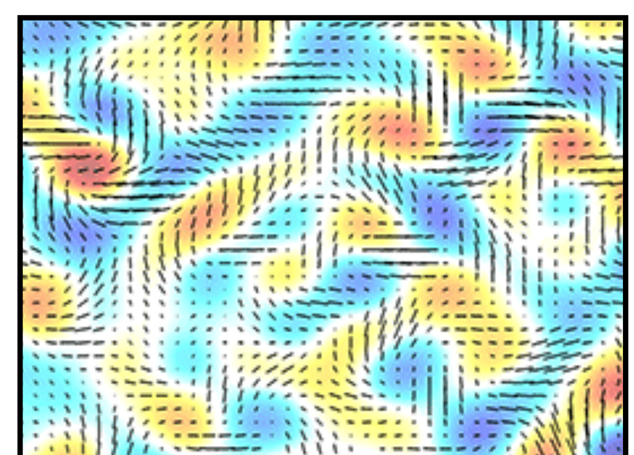

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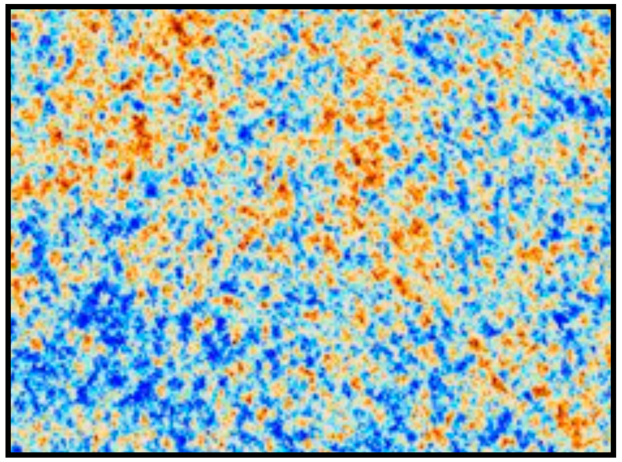

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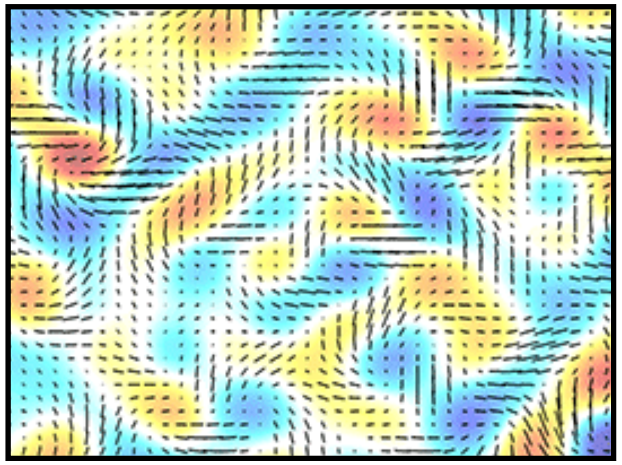
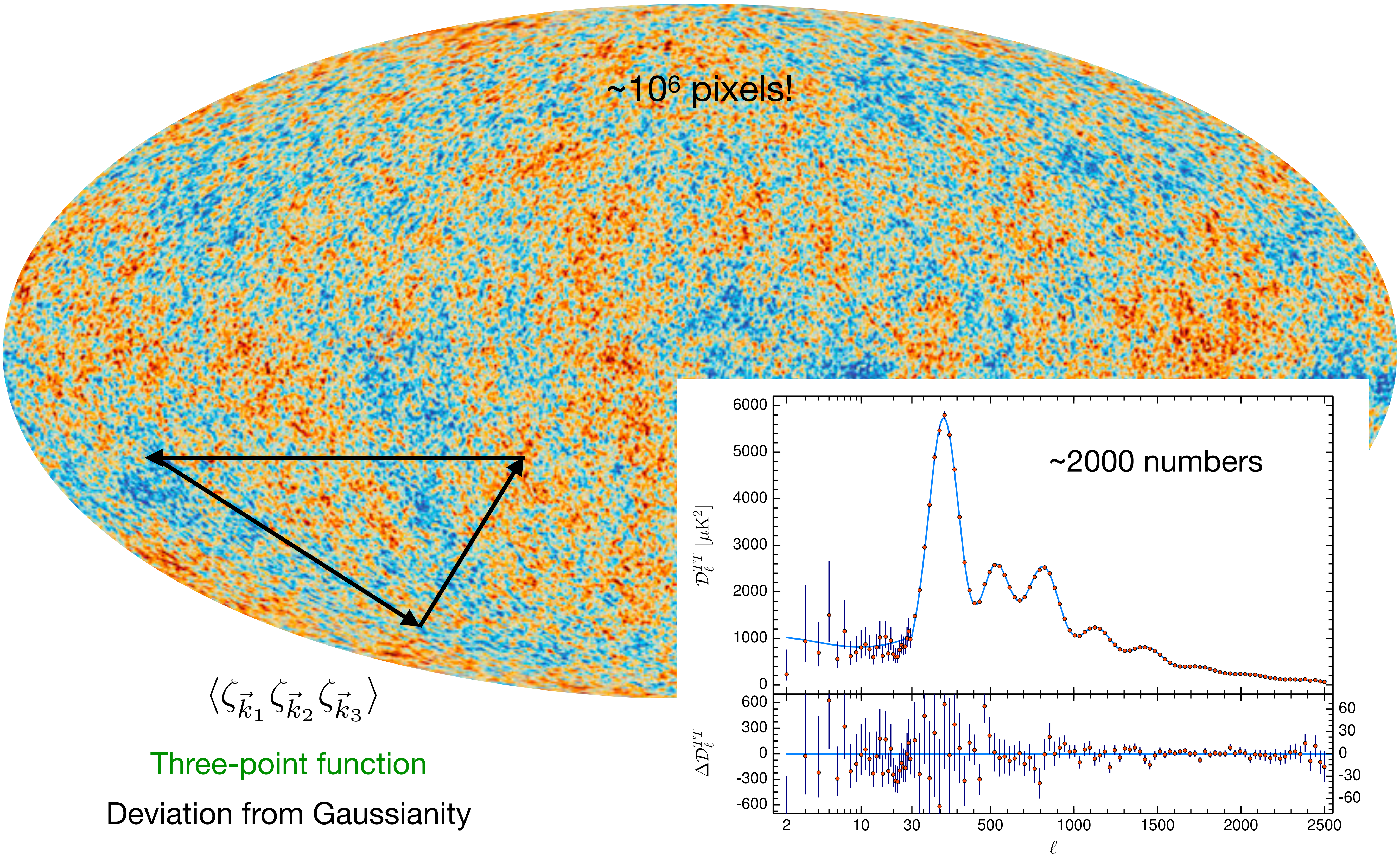


Primordial fluctuations



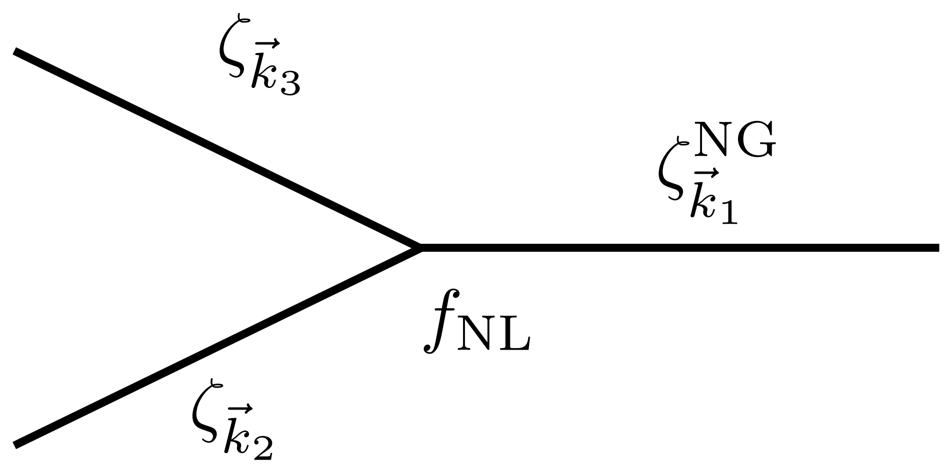
$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle$$

Three-point function

Deviation from Gaussianity

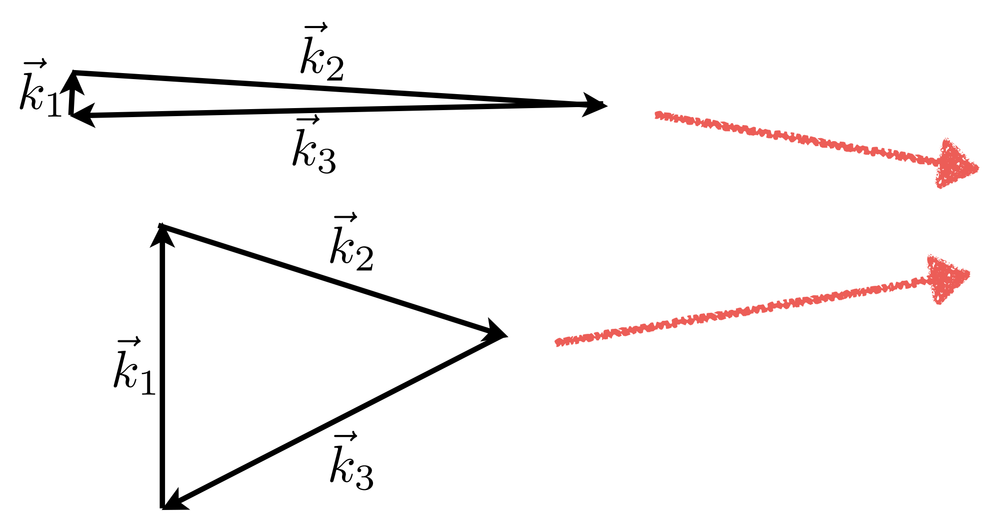
Non-Gaussianity

Probe of interactions during inflation. Suppressed by smallness of fluctuations:



$$\sim f_{\rm NL} \times A_s \, \zeta_{\vec{k}_1}$$

- Current 1σ constraints (Planck 2019):



Shape	Lensing subtracted
Local	-0.9 ± 5.1
Equilateral	-26 ± 47
Orthogonal	-38 ± 24

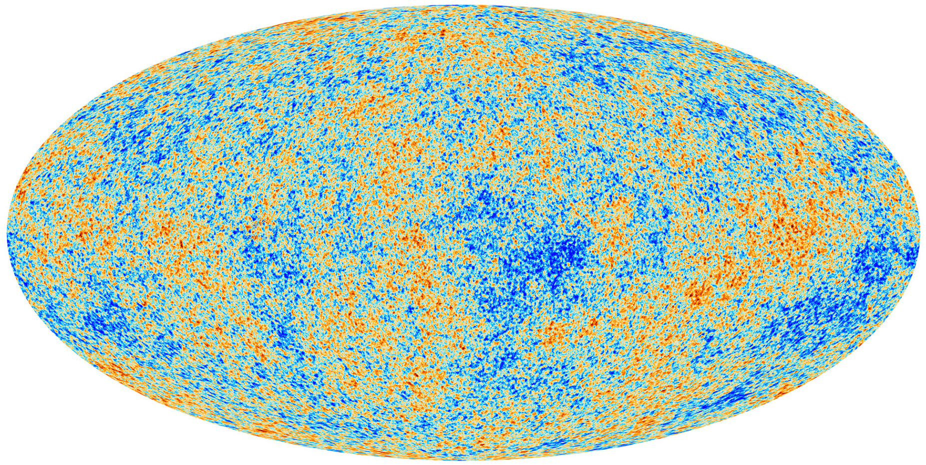
Temperature + polarization

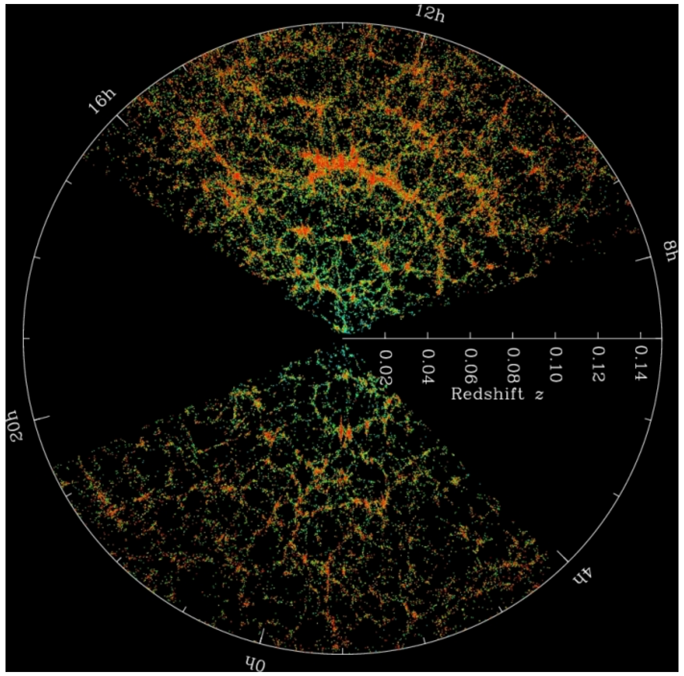
$$\frac{\text{non-Gaussian}}{\text{Gaussian}} \sim f_{\rm NL} \times A_s \lesssim 10^{-3} \div 10^{-4}$$

Future of Non-Gaussianity

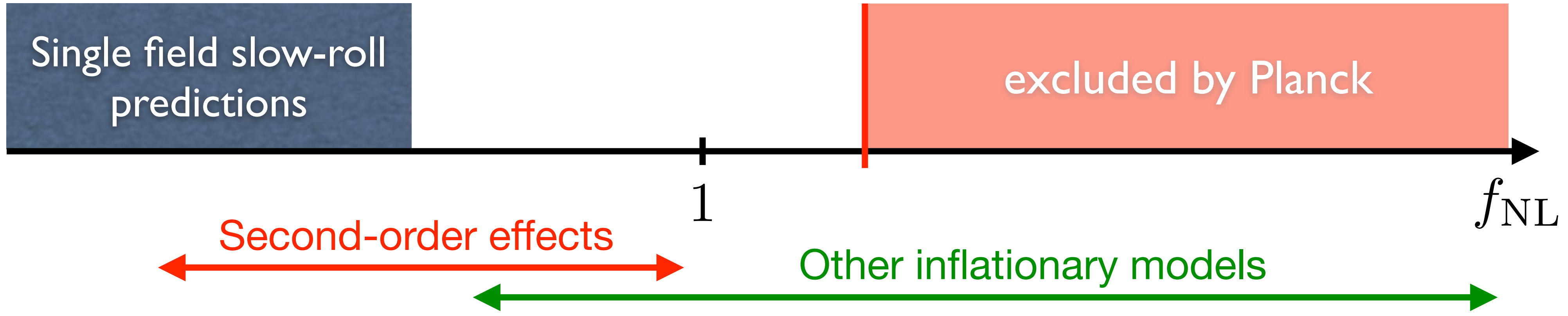
Constraints are statistical in nature:

$$\Delta f_{\rm NL} \sim \frac{10^4}{N_{\rm modes}^{1/2}}$$

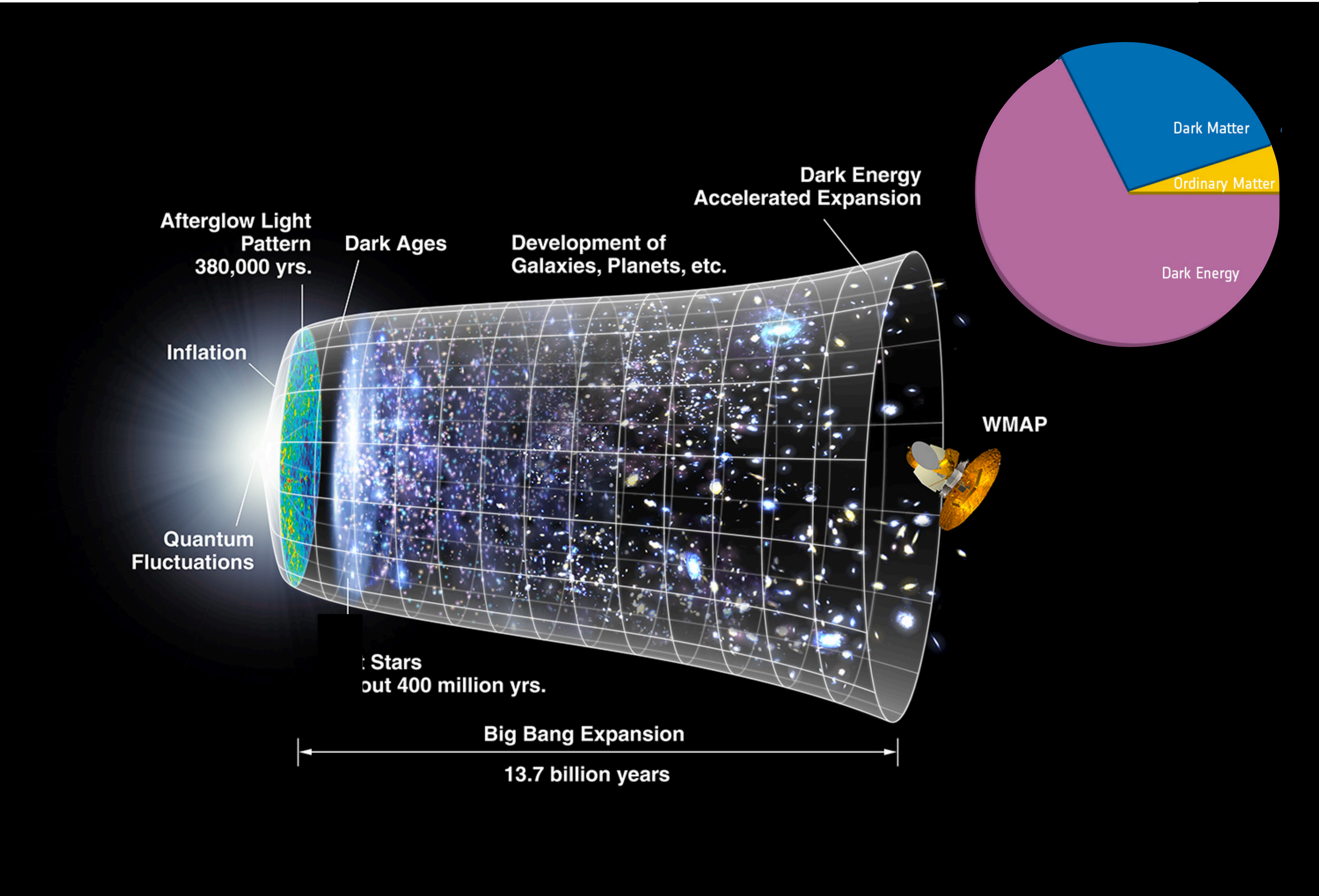




- Future experimental target, reachable by CMB + LSS:
  - $f_{\rm NL}^{\rm loc} \lesssim 1$ single-clock
  - $f_{\rm NL}^{\rm eq} \lesssim 1$ slow-roll

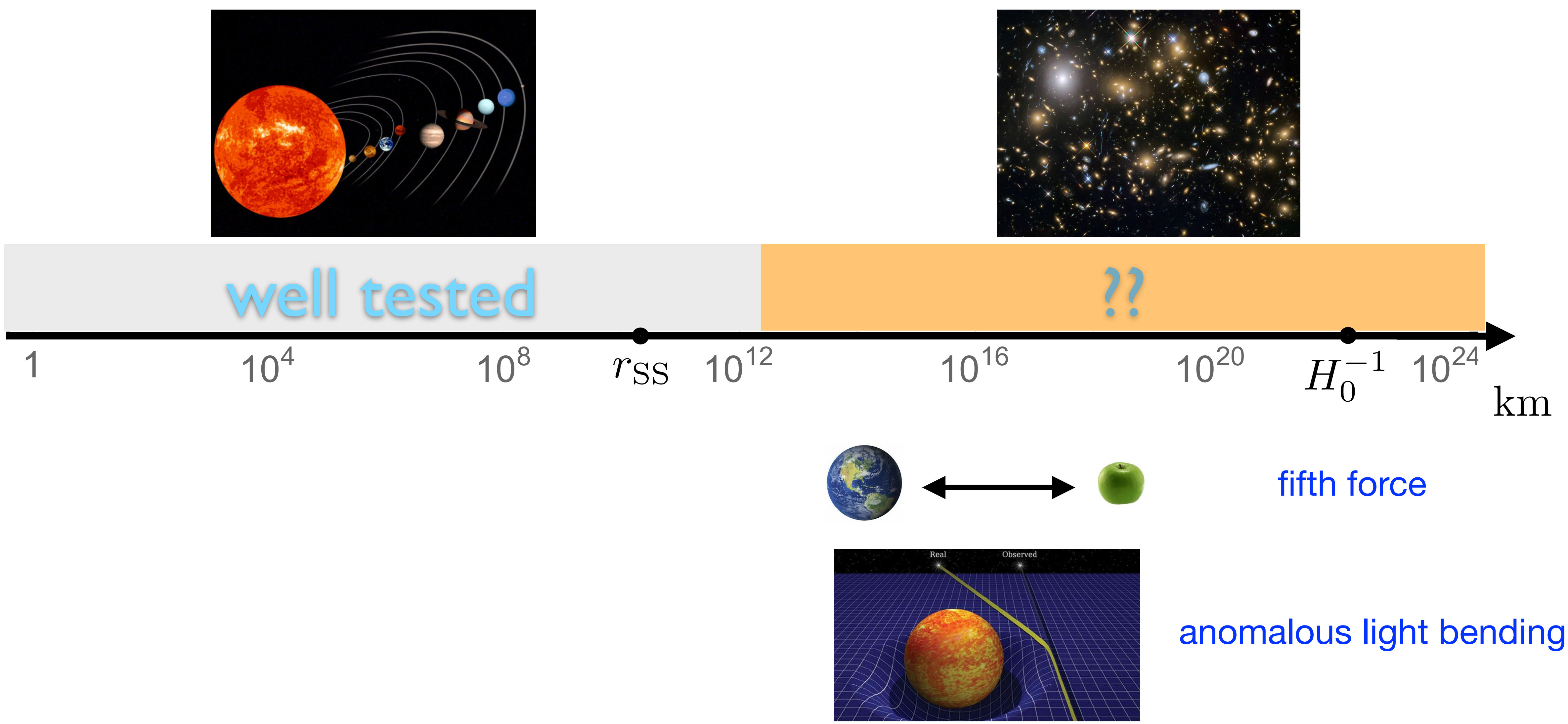


Standard cosmological model



Open questions

- What is the origin of the accelerated expansion?
- New component or a modification of gravity on large scales?
- Can we improve our tests of General Relativity on cosmological scales?
- ...



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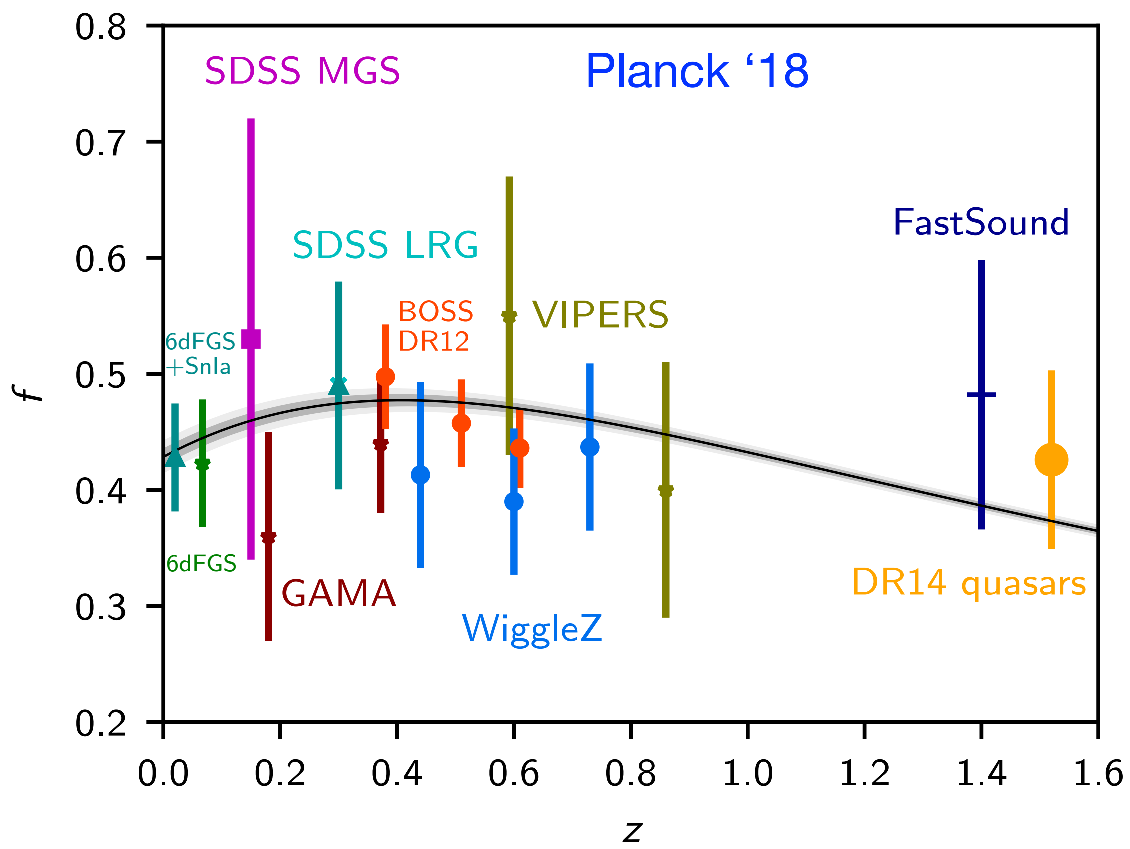

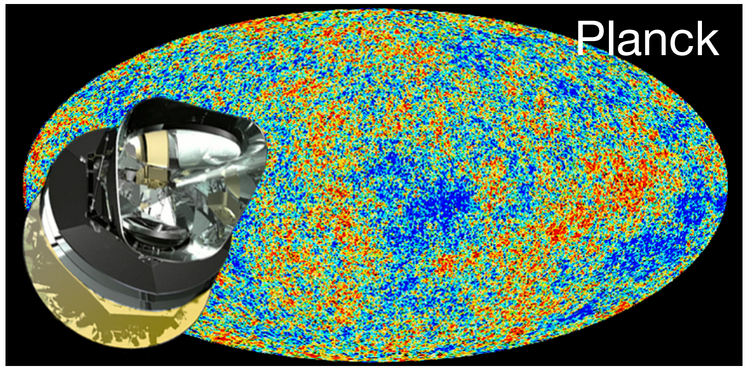

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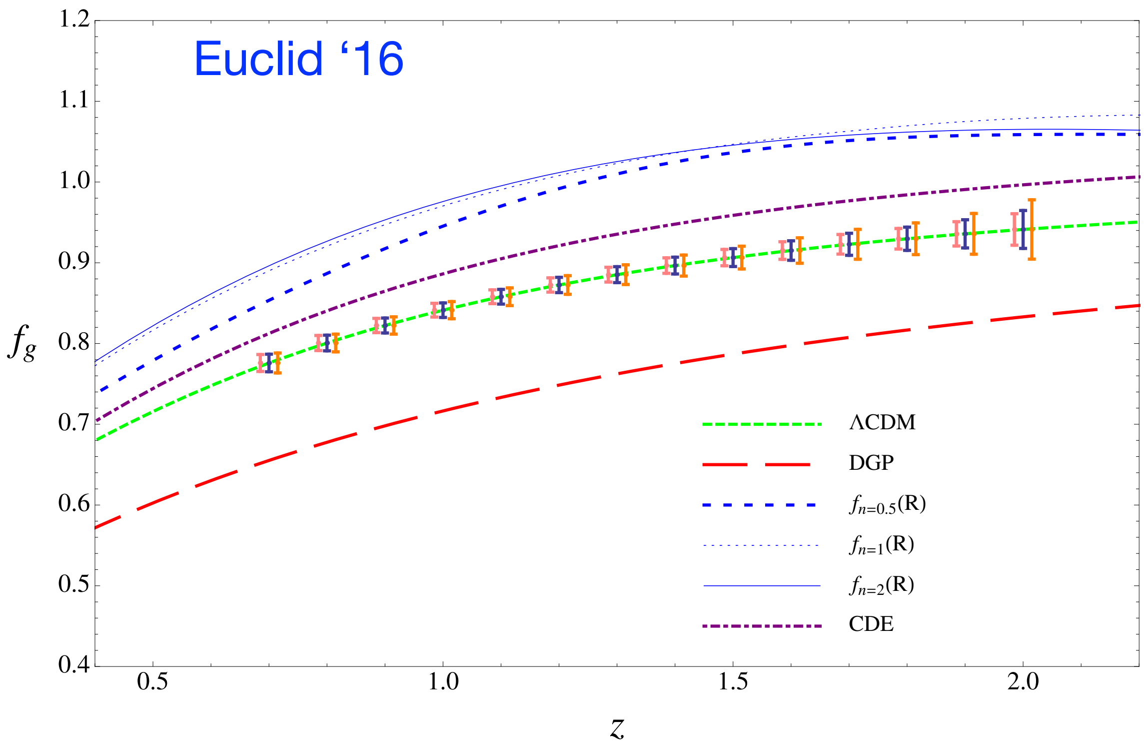
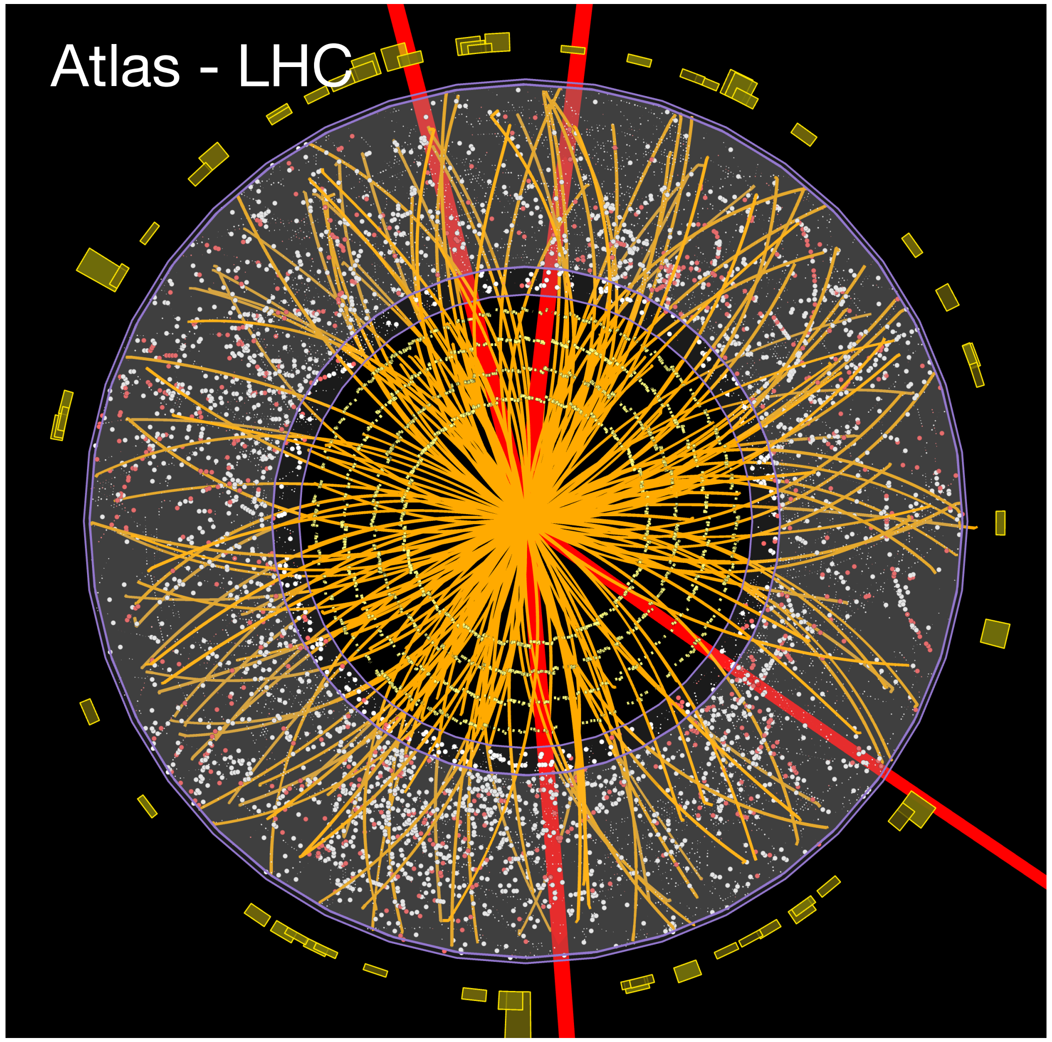
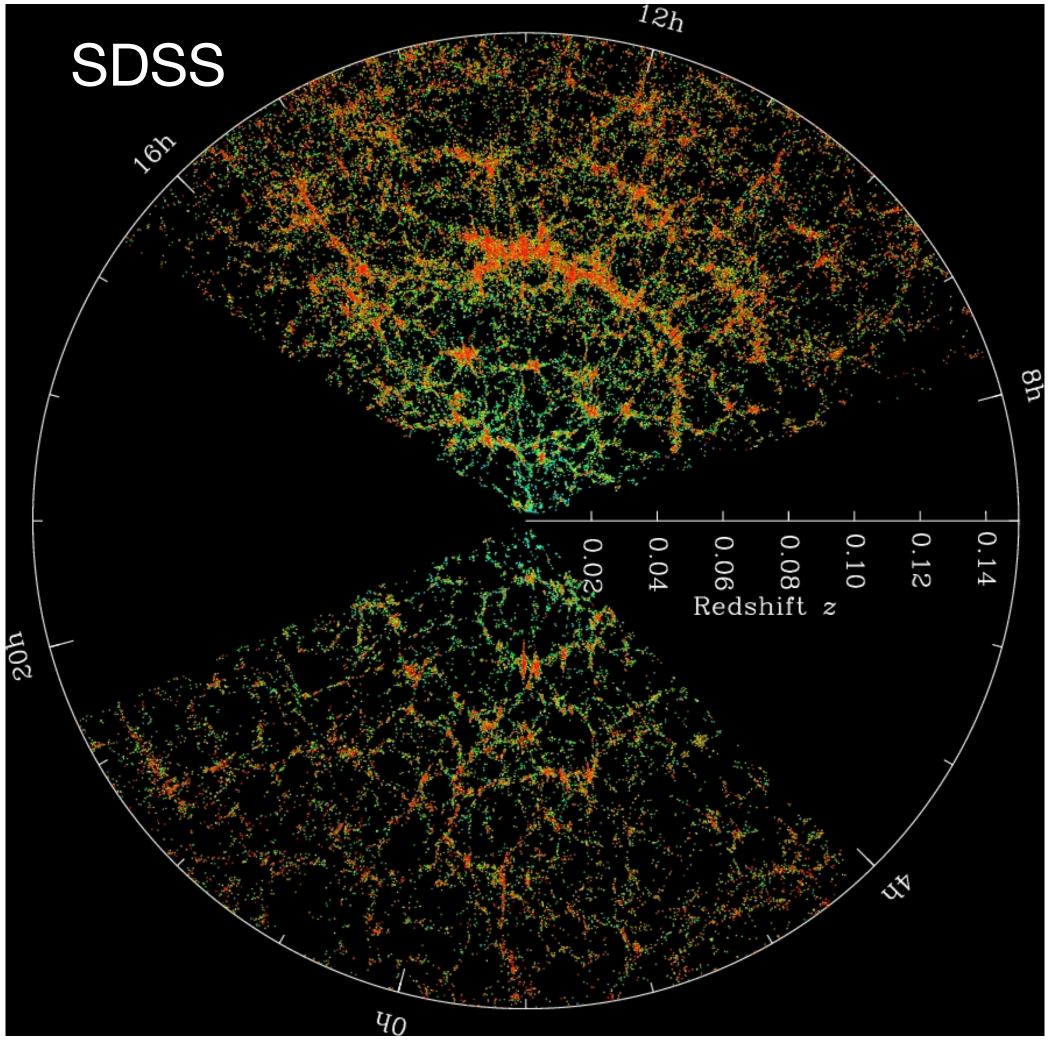


Precision tests

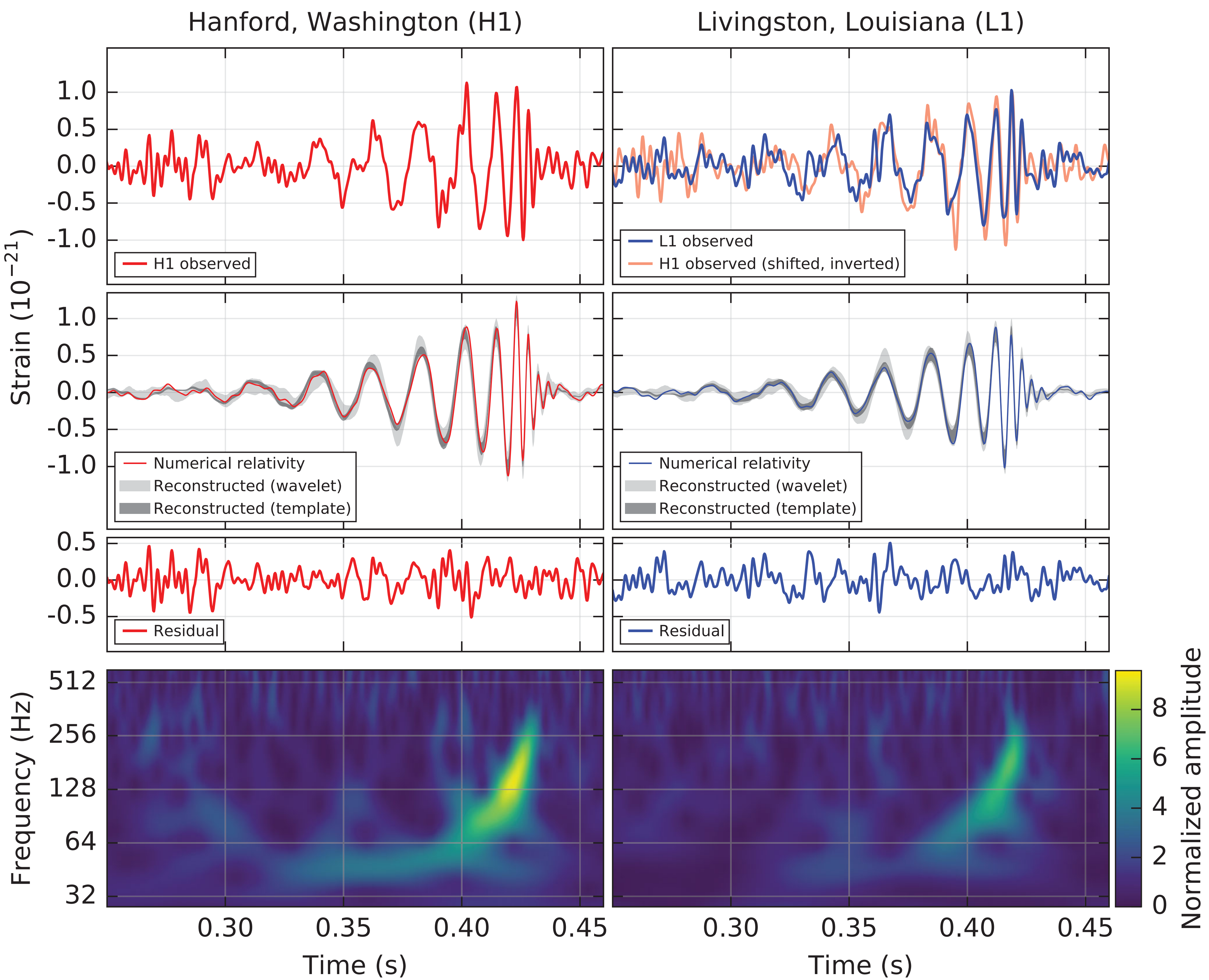
Cosmological precision tests of the Standard Model of cosmology (similar to precision tests of the Standard Model of particle physics at the LHC)



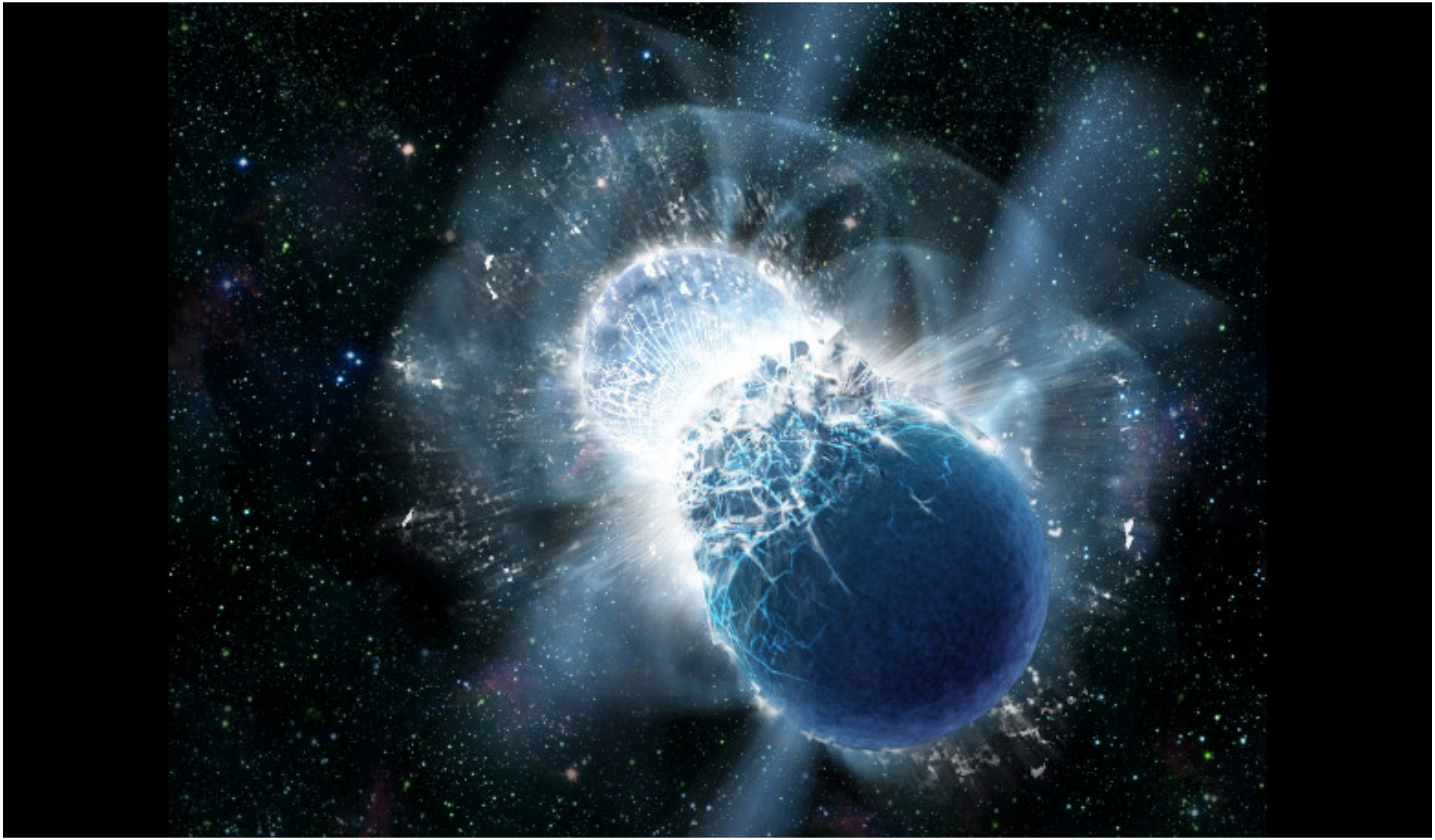


GW140915: Gravitational Waves

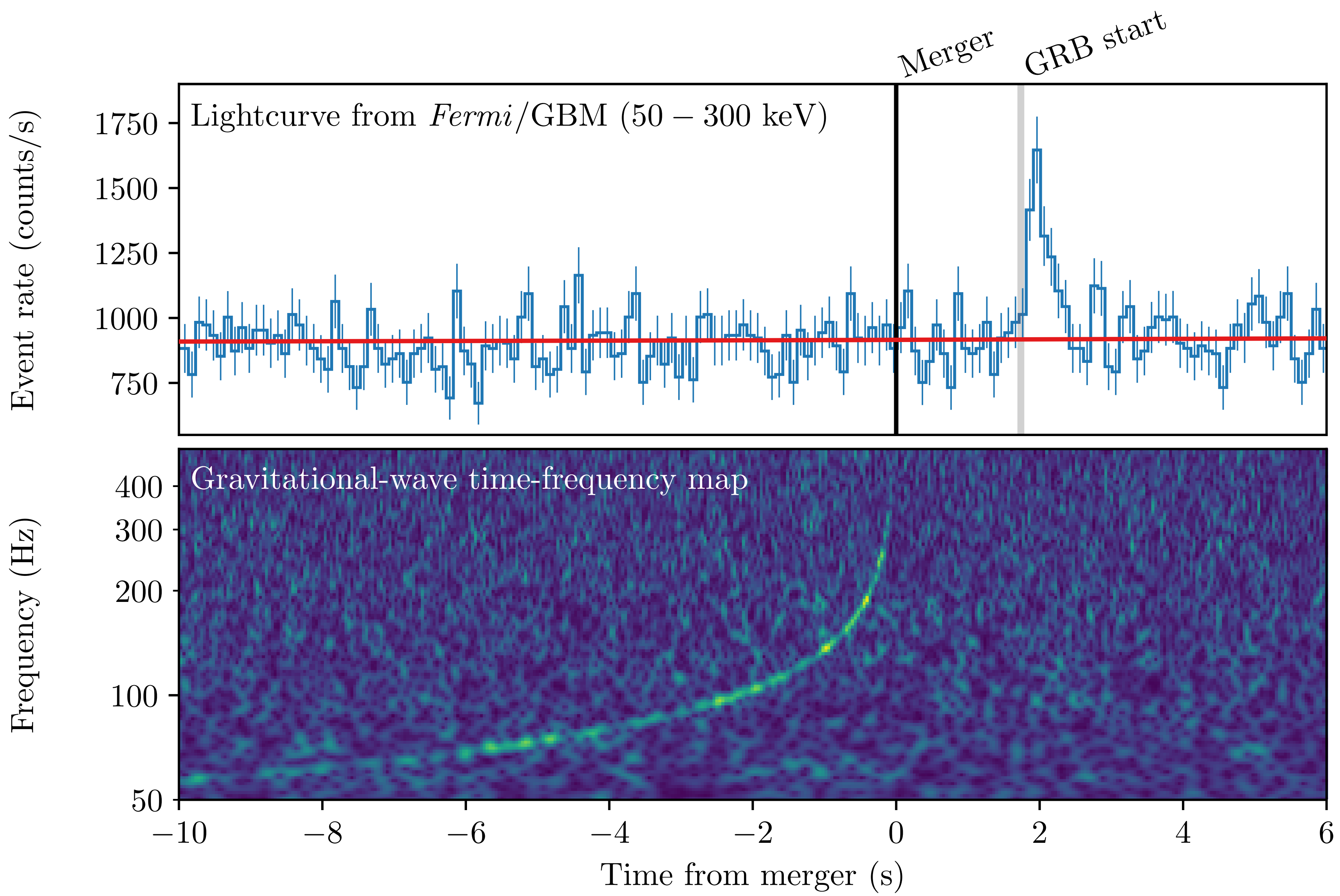
Abbott et al. '16
first detection: 09/14, 2015



GW170817: neutron star merger



Multi-messenger observation



$$-3 \times 10^{-15} \leq \frac{c_T - c}{c} \leq 7 \times 10^{-16}$$

Gravitational wave equation

Gravitational wave equation:

$$ds^2 = -dt^2 + a^2(t)\left[\delta_{ij} + \gamma_{ij}\right] d\vec{x}^i d\vec{x}^j \ , \qquad \gamma_{ii} = 0 = \partial_i \gamma_{ij} \ , \qquad H = \dot{a}/a$$

$$\ddot{\gamma}_{ij}^{\lambda} + 3H\dot{\gamma}_{ij}^{\lambda} + k^2 \gamma_{ij}^{\lambda} = 16\pi G\, S_{ij}^{\lambda} \ , \qquad \lambda = +, \times$$

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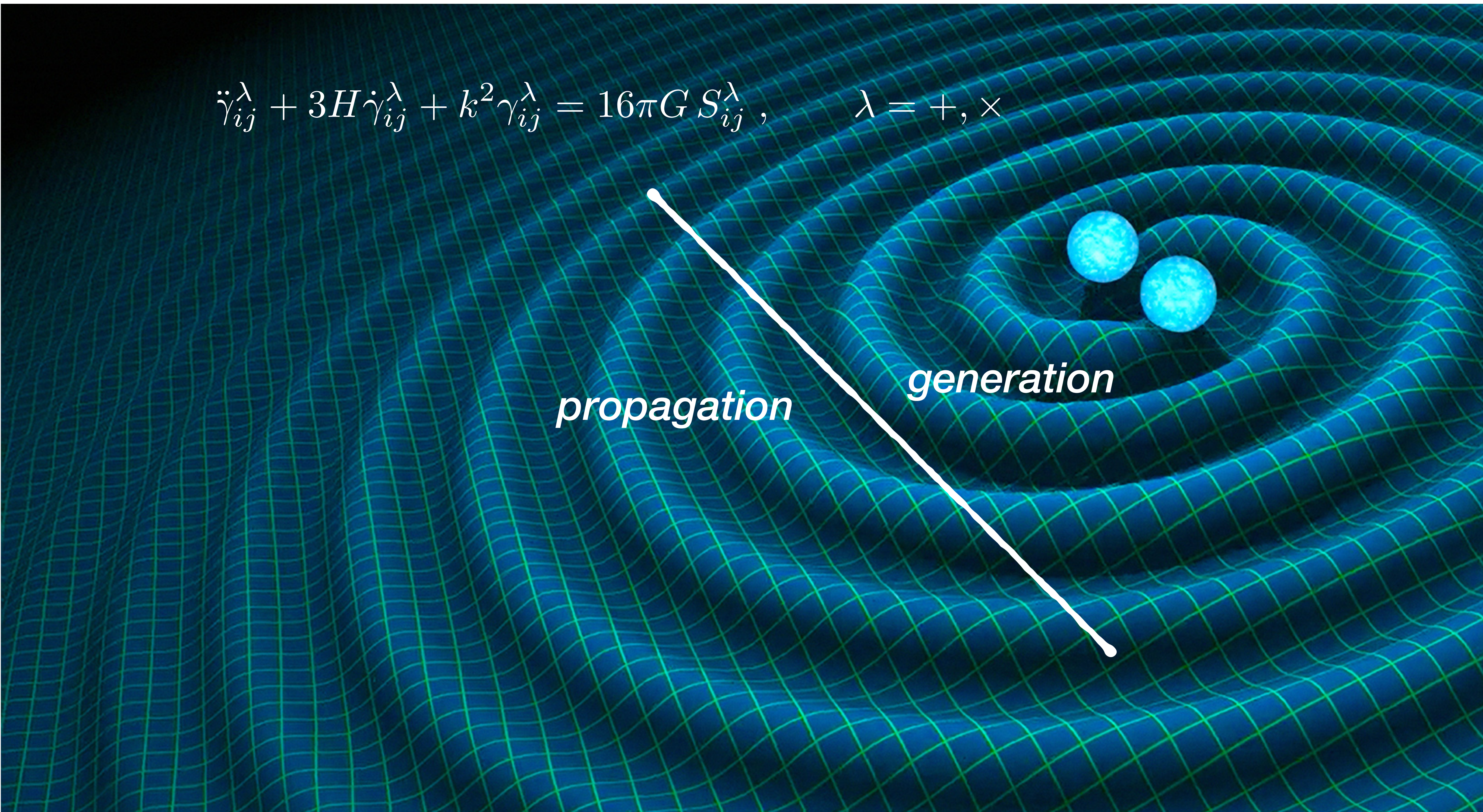
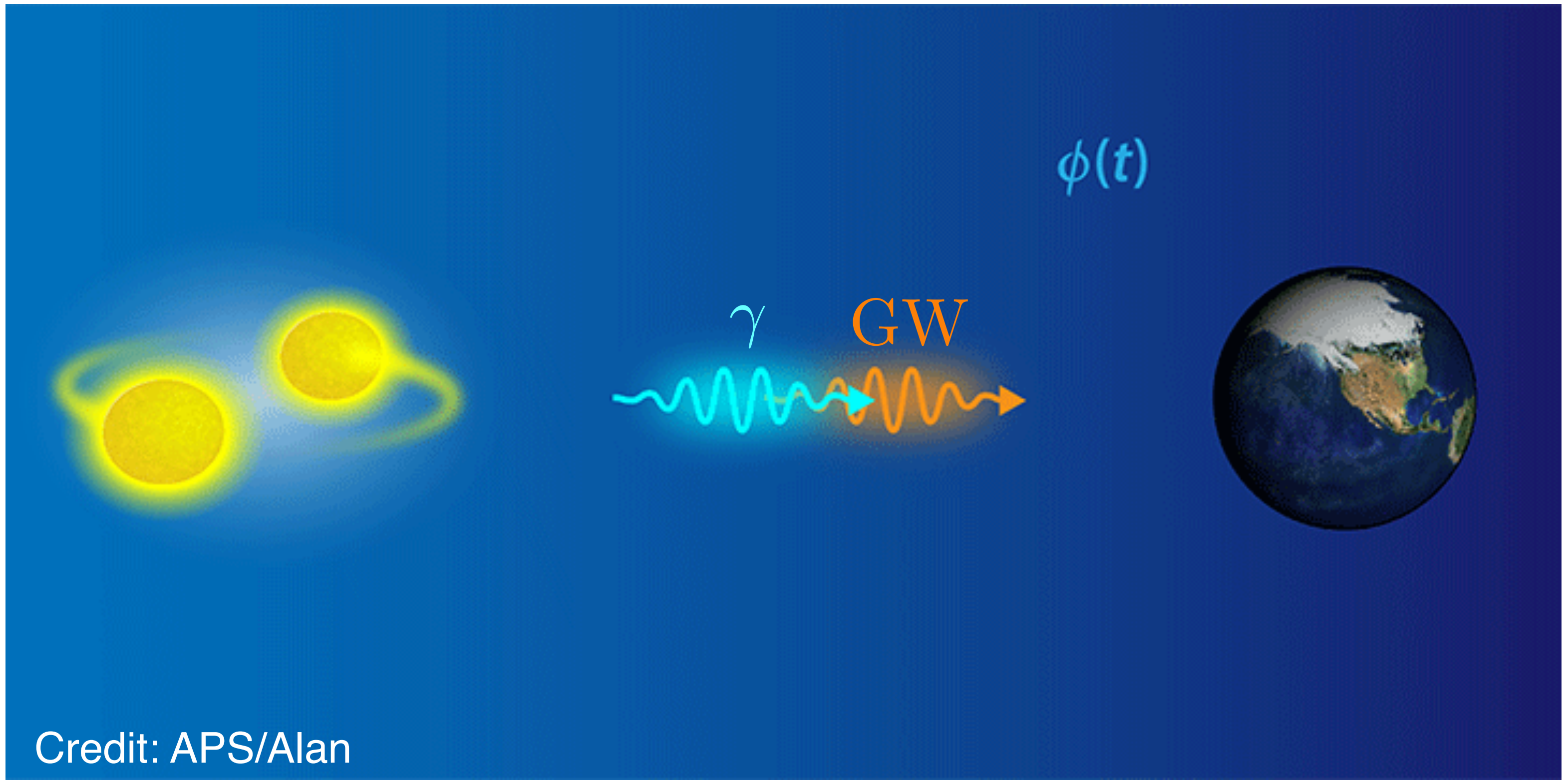


Modified gravitational wave propagation

Modified gravity spontaneously breaks Lorentz Invariance. Acts like a medium, where gravitons are absorbed and dispersed. Effects accumulate on long time-scale.

$$\ddot{\gamma}_{ij}^{\lambda} + H\left[3 + \ldots\right]\dot{\gamma}_{ij}^{\lambda} + \left[c_T^2 k^2 + \ldots\right]\gamma_{ij}^{\lambda} = 0$$



Generalized scalar-tensor theories

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \qquad \Box\phi \equiv \phi_{;\mu}^{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

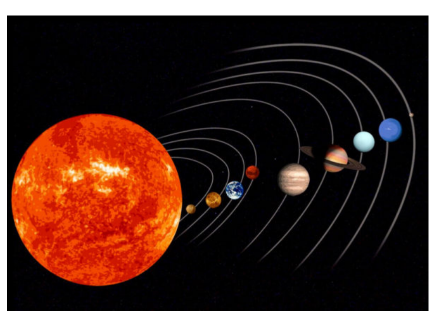
$$- 2G_{4,X}(\phi, X)\Big[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\Big]$$

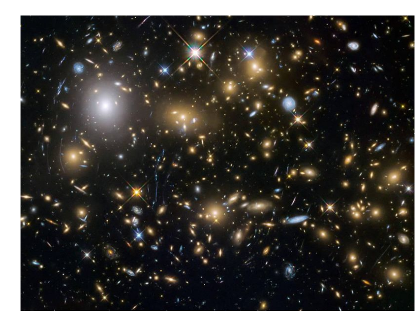
$$+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\Big[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\Big]$$

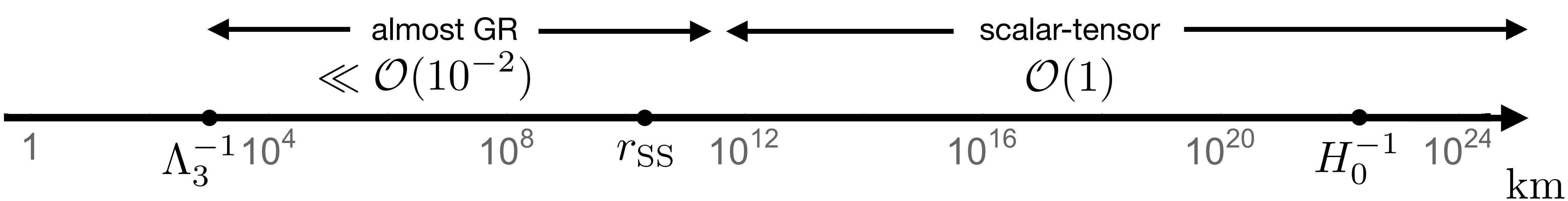
$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$- F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}$$

Self-acceleration and screening: large classical scalar field nonlinearities







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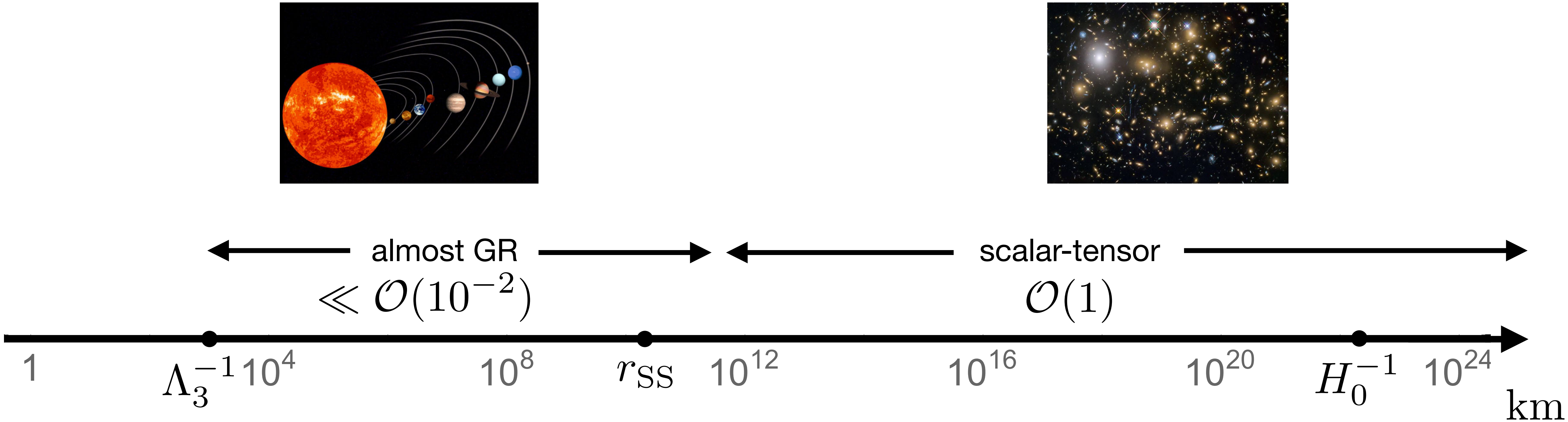

Conclusion

- Well establish Standard Model of cosmology but still open questions: What is the nature of the two accelerated phases?

- **Inflation**: Coherently supported by observations. Hopefully new surprises from future large scale structure (and B-mode polarization) data.

- **Dark energy**: Future large scale structure surveys will help us understand gravity on large scales. Gravitational waves can be used complementarily to the large scale structure in constraining models and establishing standard scenario or in unveiling new physics.