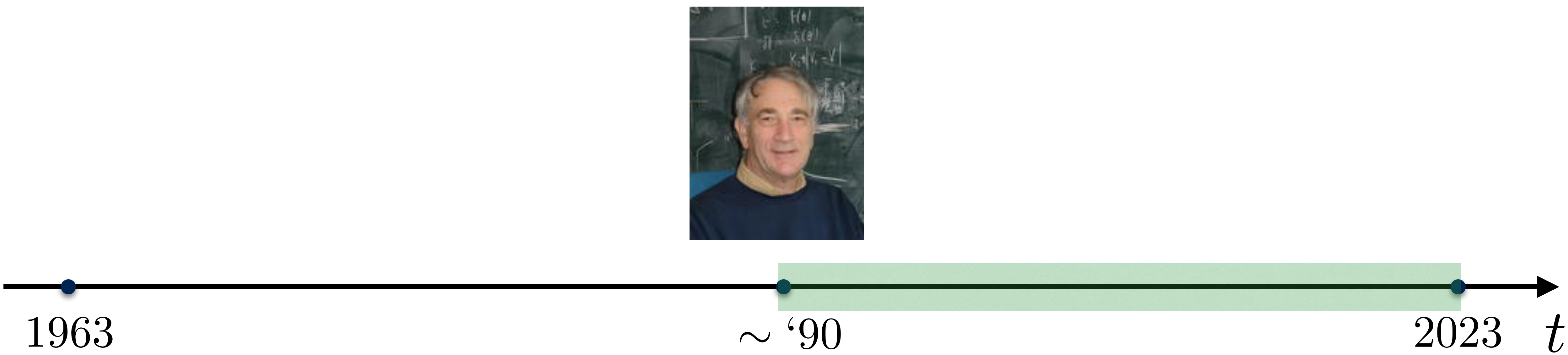
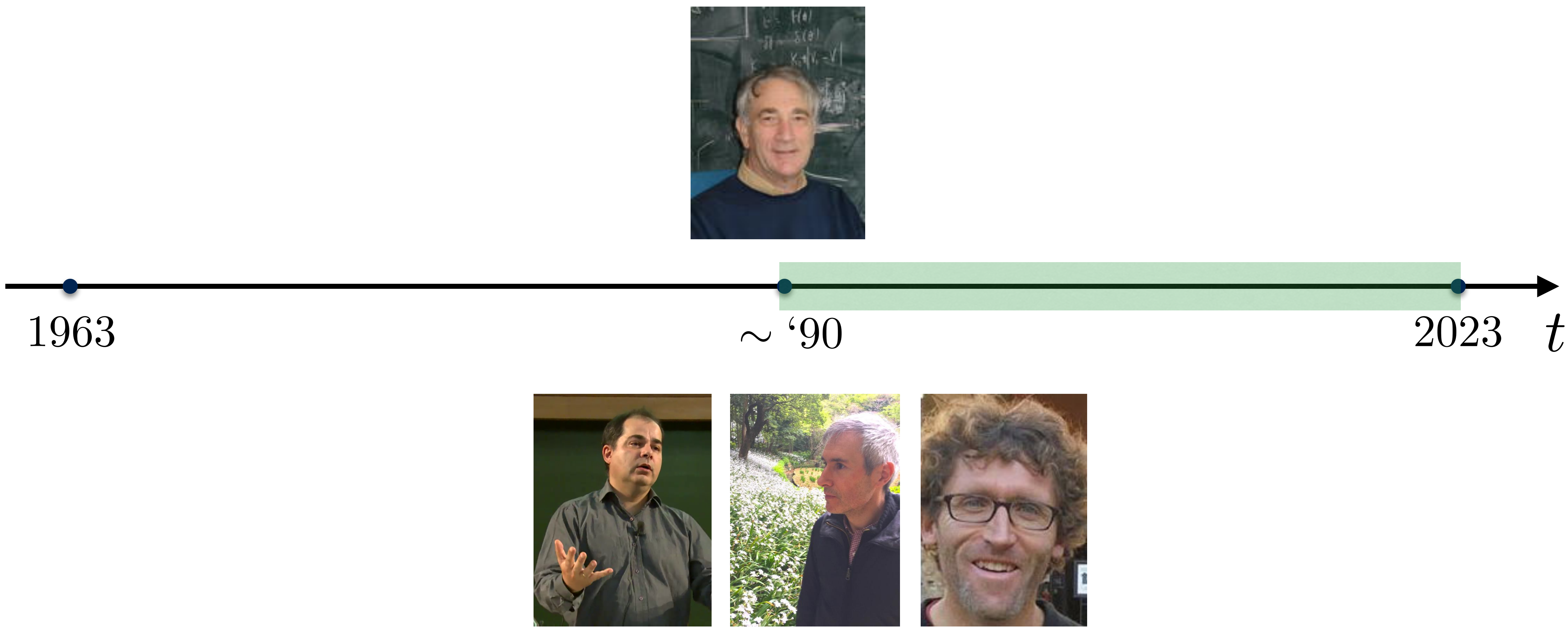
Cosmology at IPhT

Filippo Vernizzi
IPhT - CEA, CNRS, Paris-Saclay

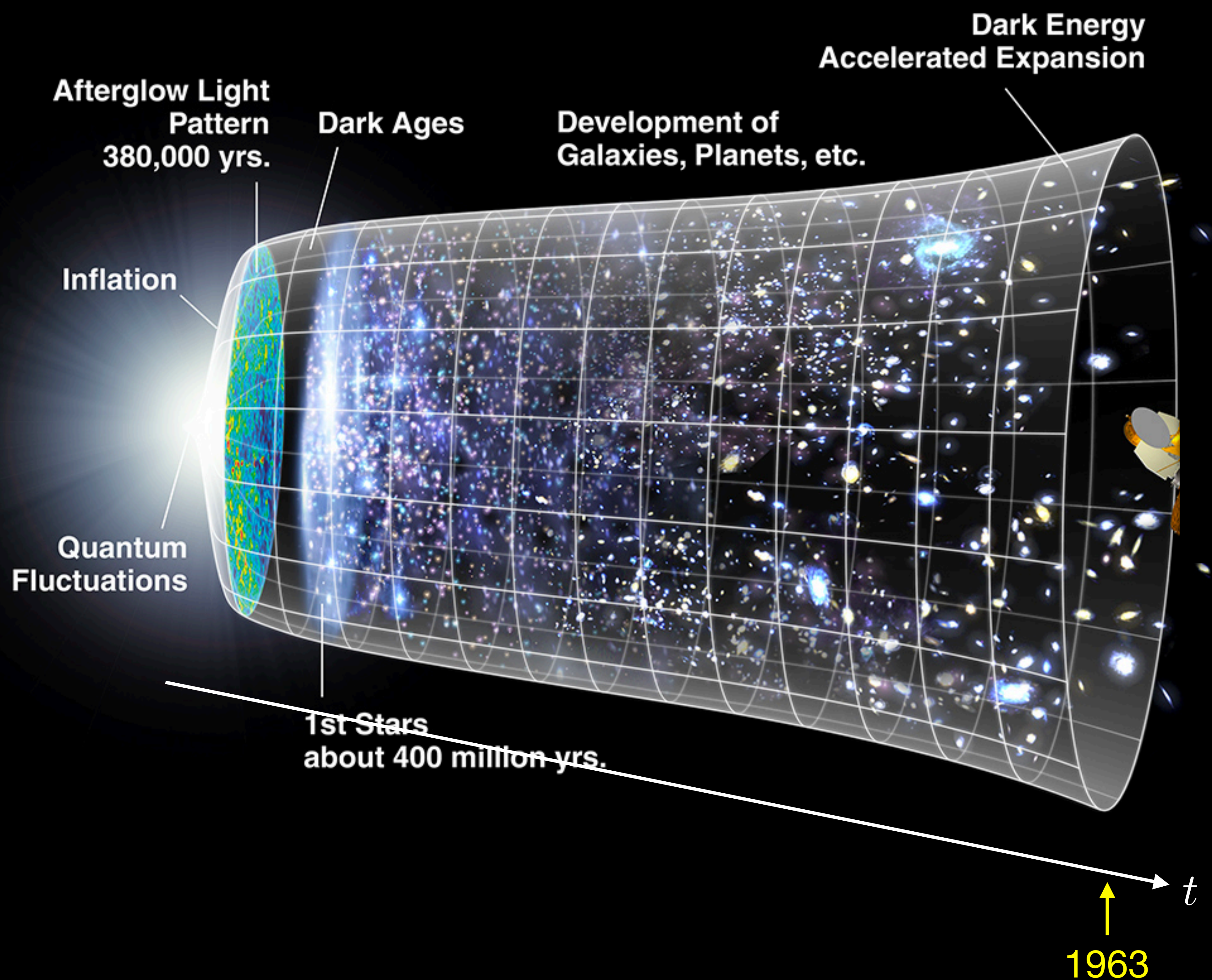
10 Novembre 2023
“Célébration des 60 ans de l’IPhT”


1963
2023
t


1963
$\sim$ '90
2023
t


1963
~ '90
2023
t

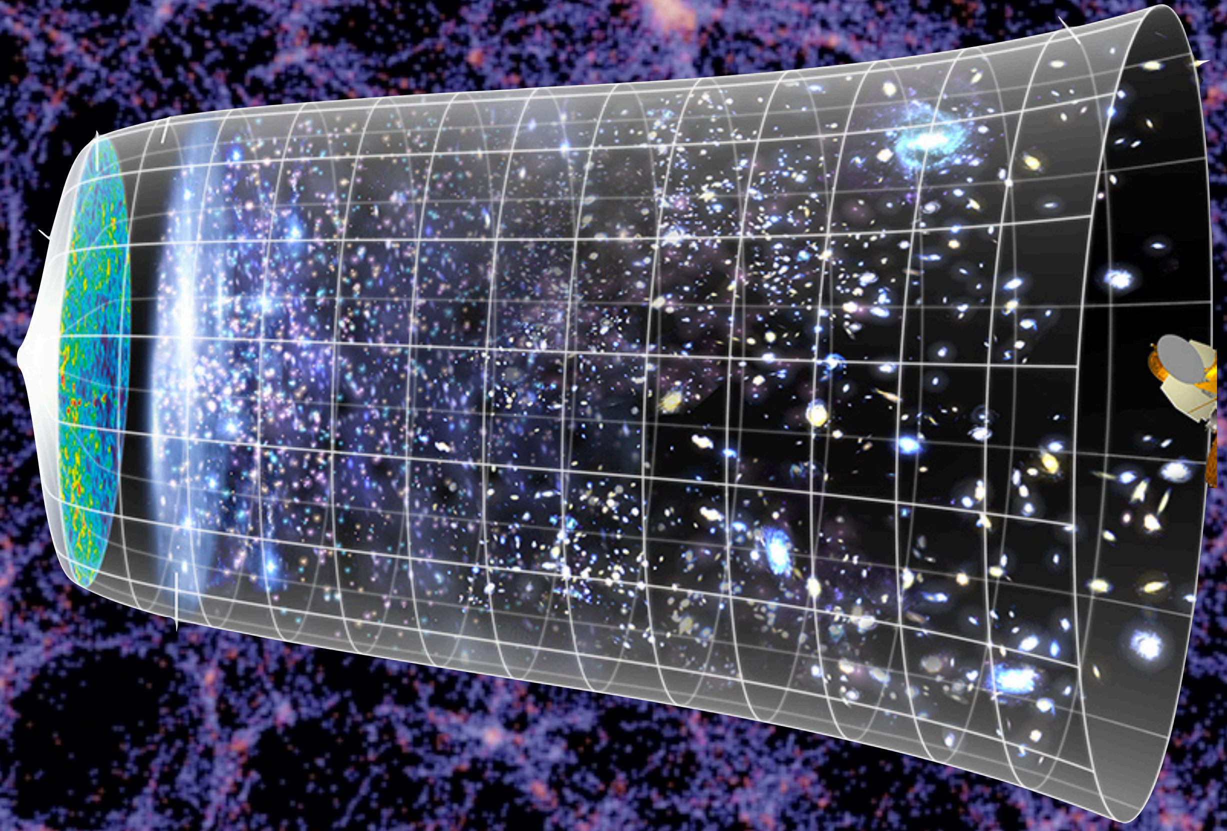
Standard cosmological model

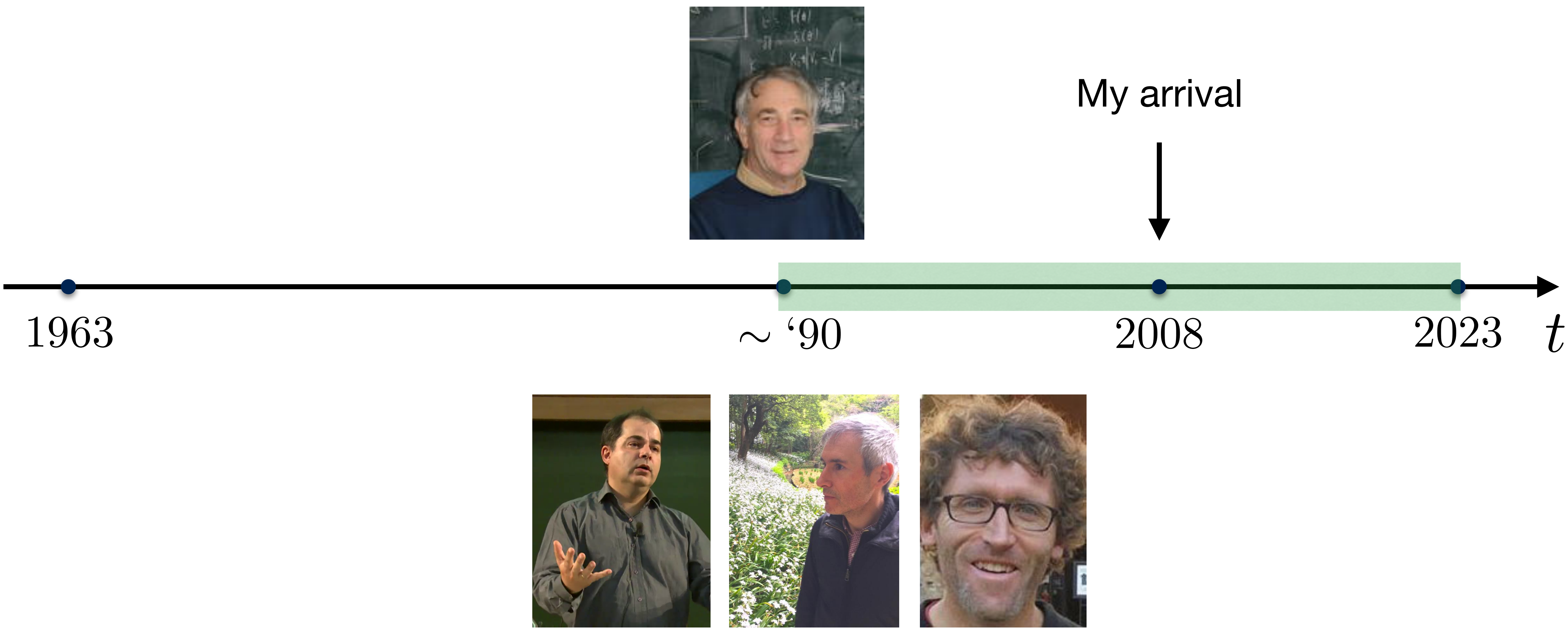


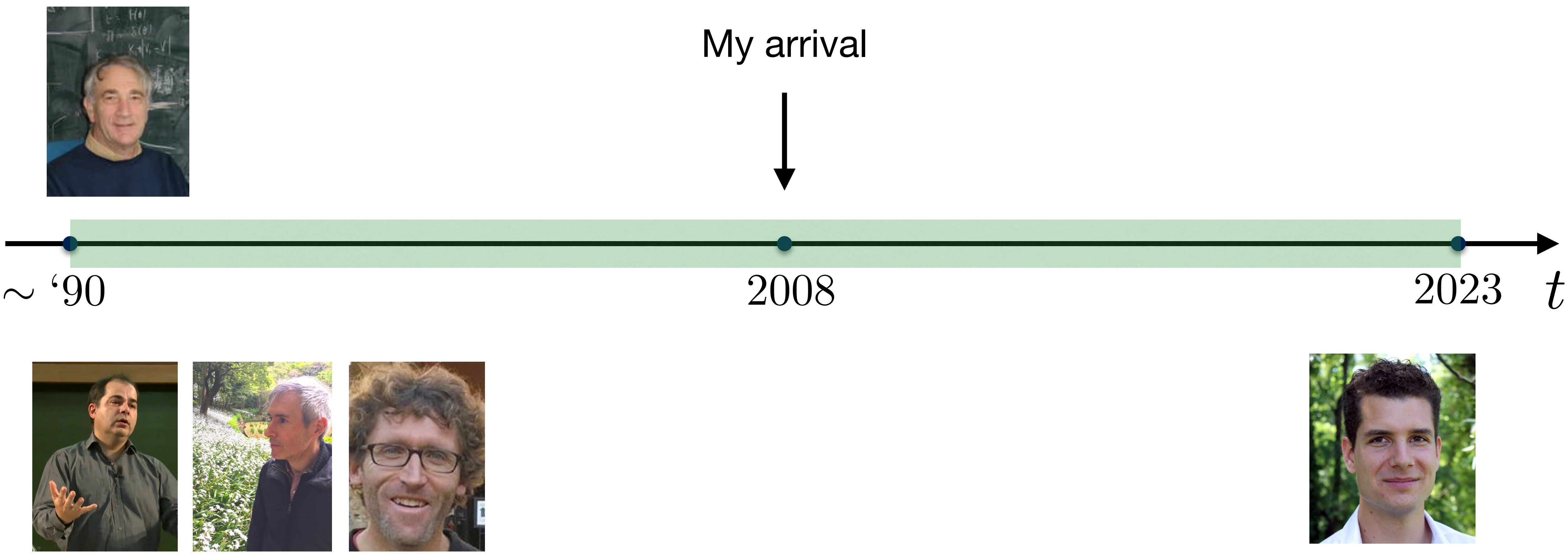
Goals of cosmology today

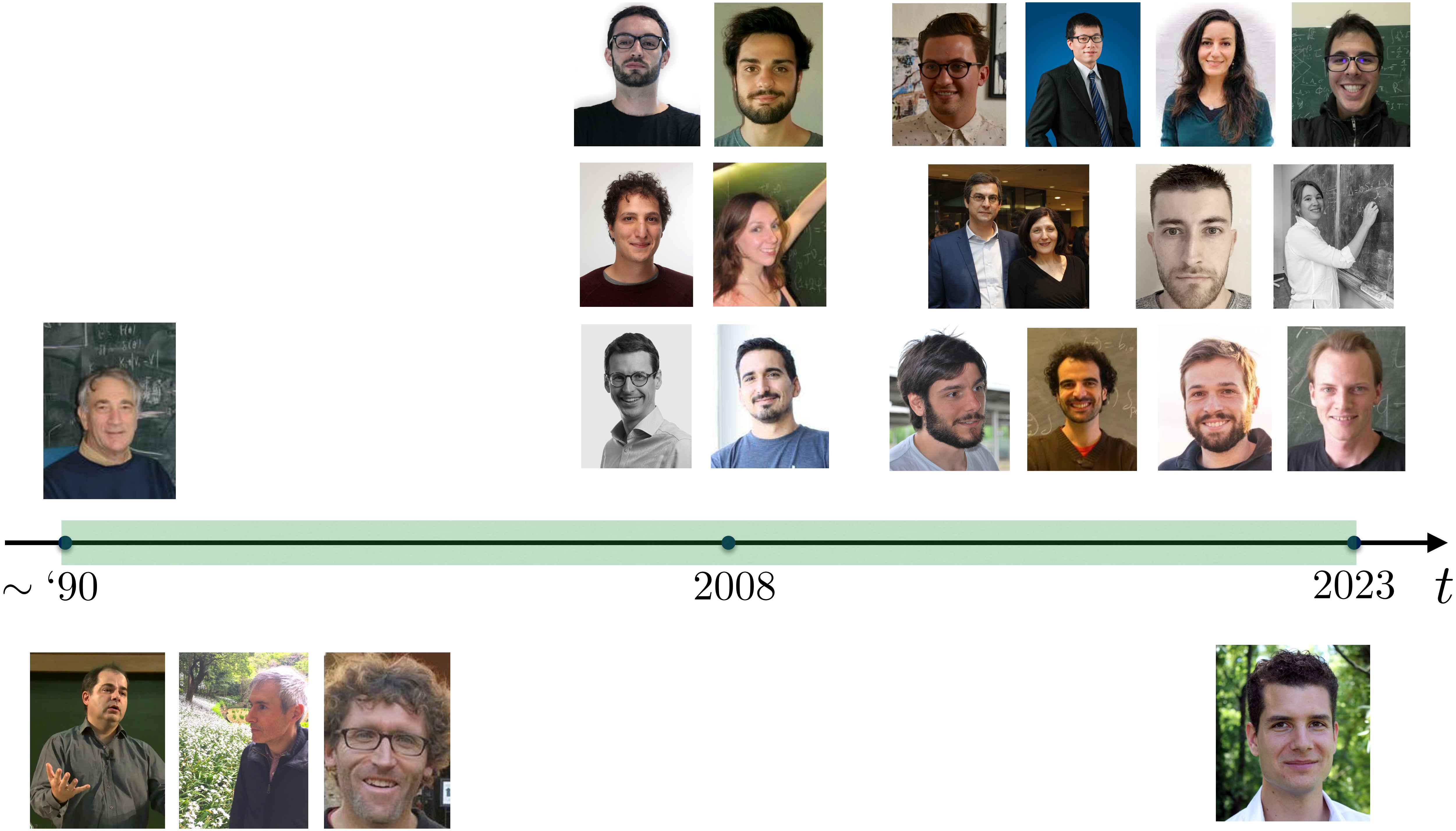
Answer these questions:

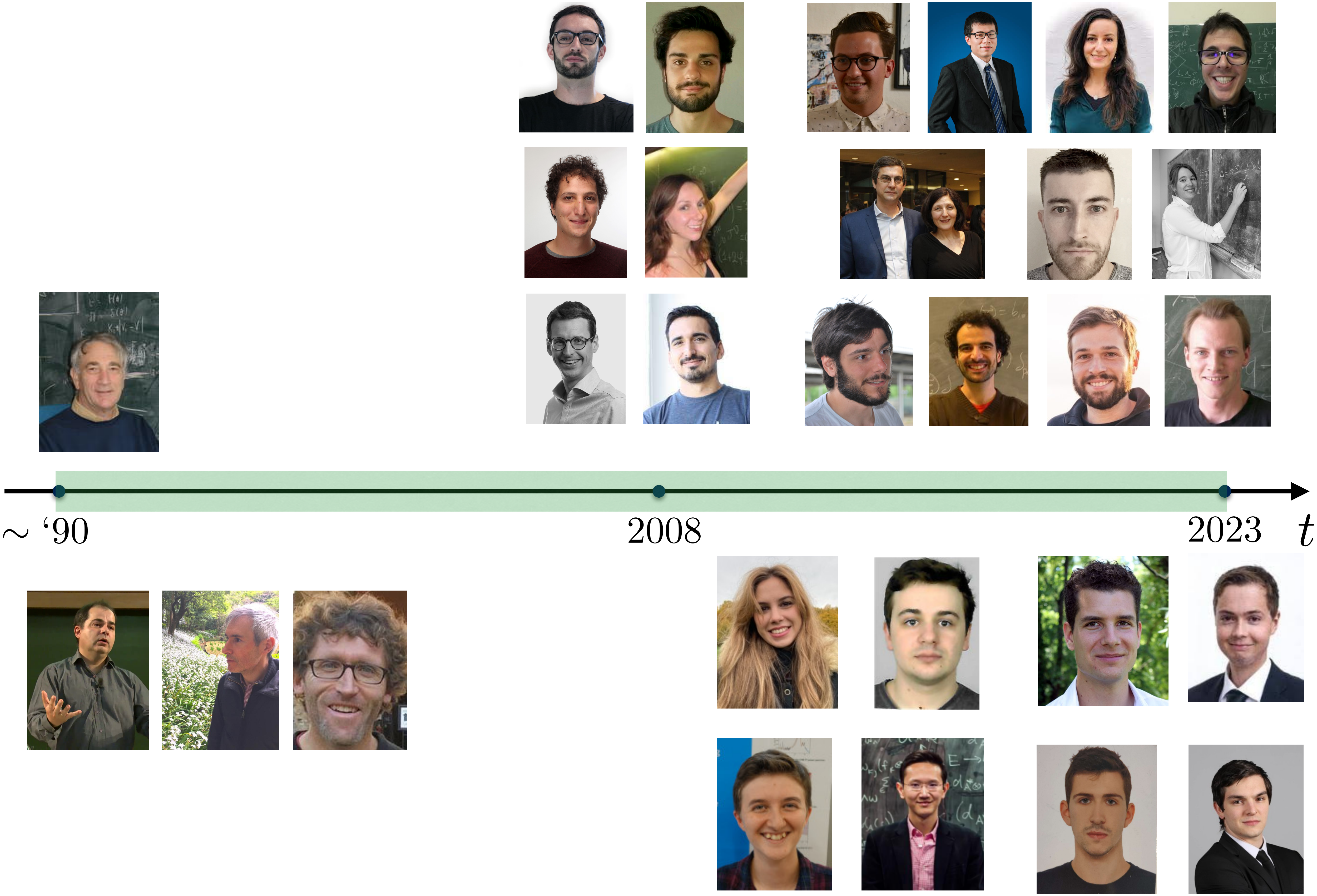
- How did the Universe begin (inflation, one or many fields, etc.) and what is its history (expansion history, thermal history, etc.)
- What is it made of (usual matter, dark matter, dark energy, neutrinos, etc.)
- What are its physical laws (general relativity, modified gravity, etc.)
- …




My arrival
1963
~ '90
2008
2023
t

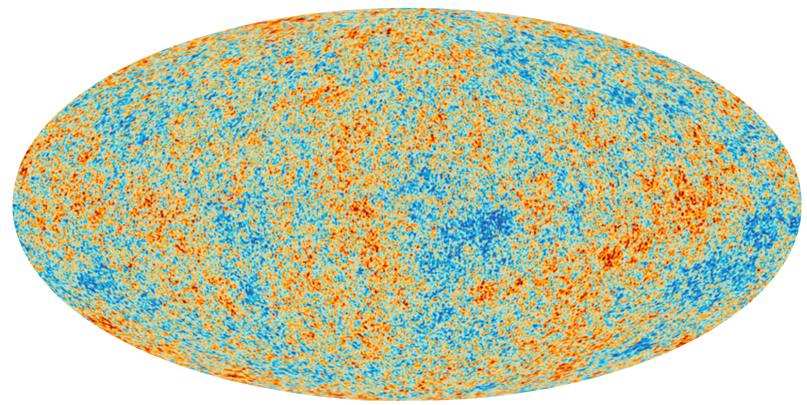

My arrival
$\sim$ '90
2008
2023
t

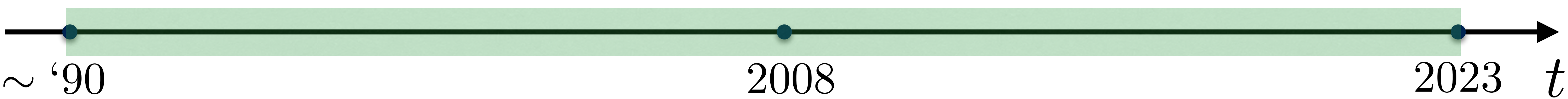

~ '90
2008
2023
t


~ ‘90
2008
2023
t

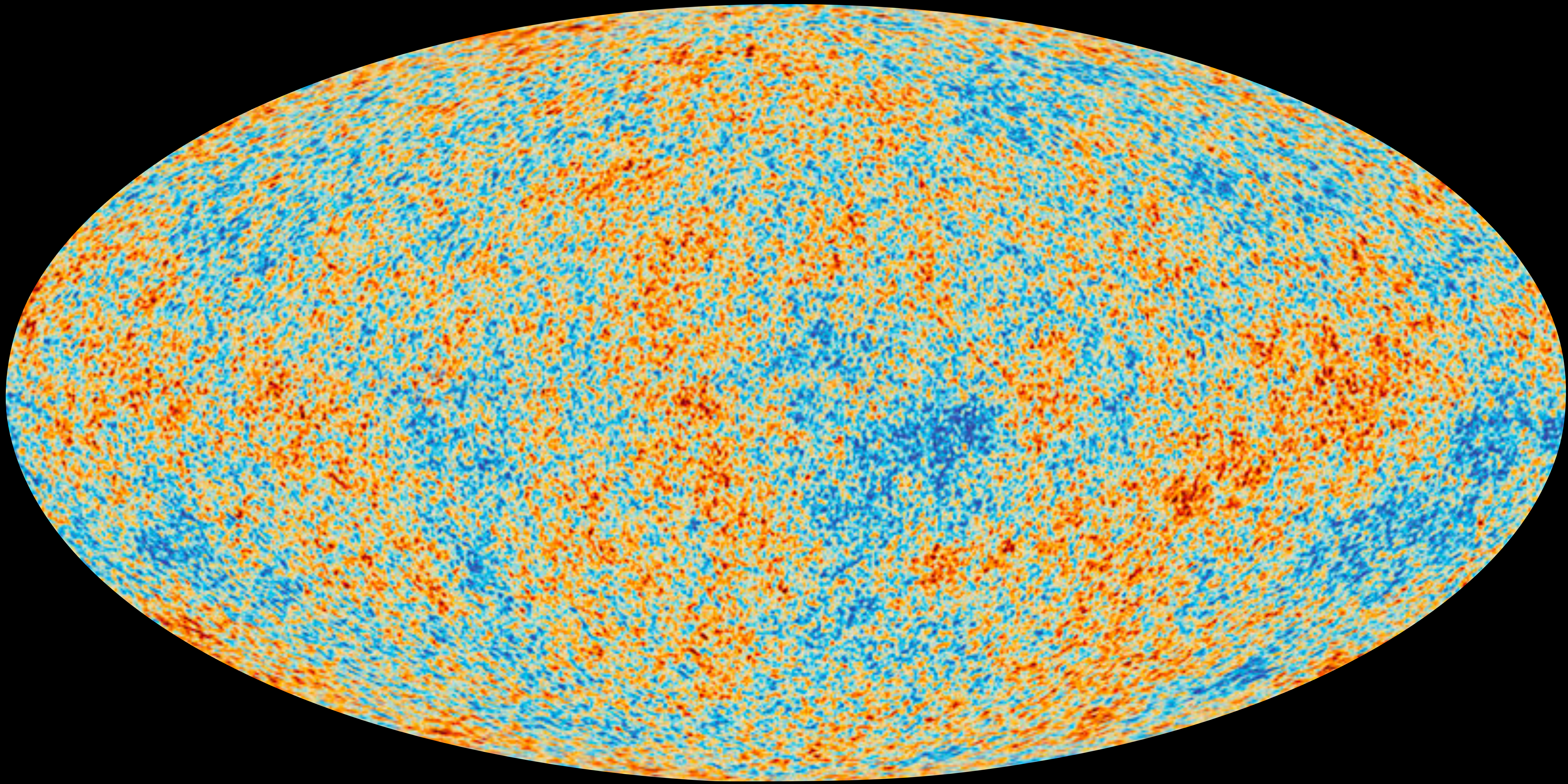
Cosmic Microwave Background:

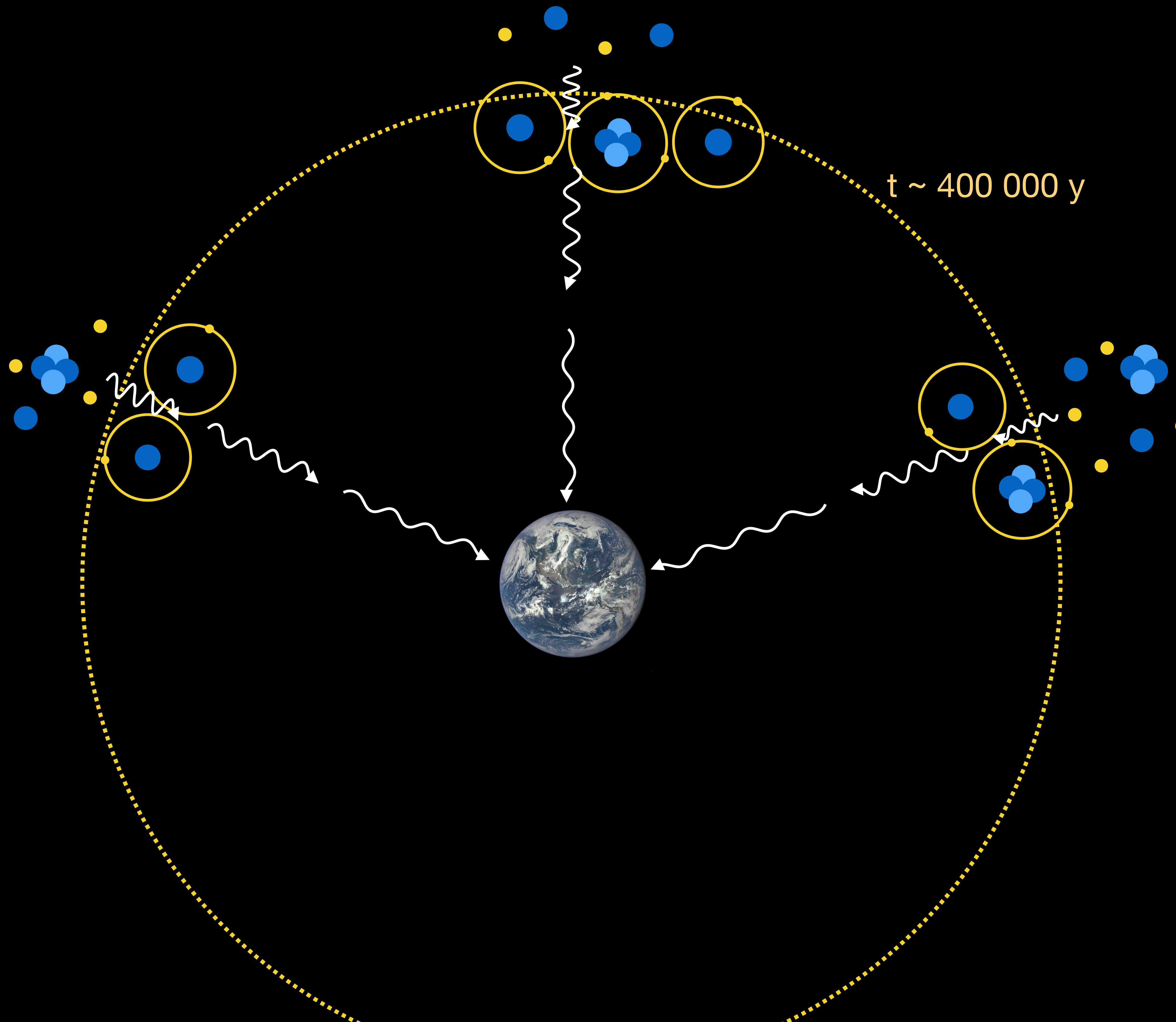
WMAP 2001-10,
Planck 2010-15, …





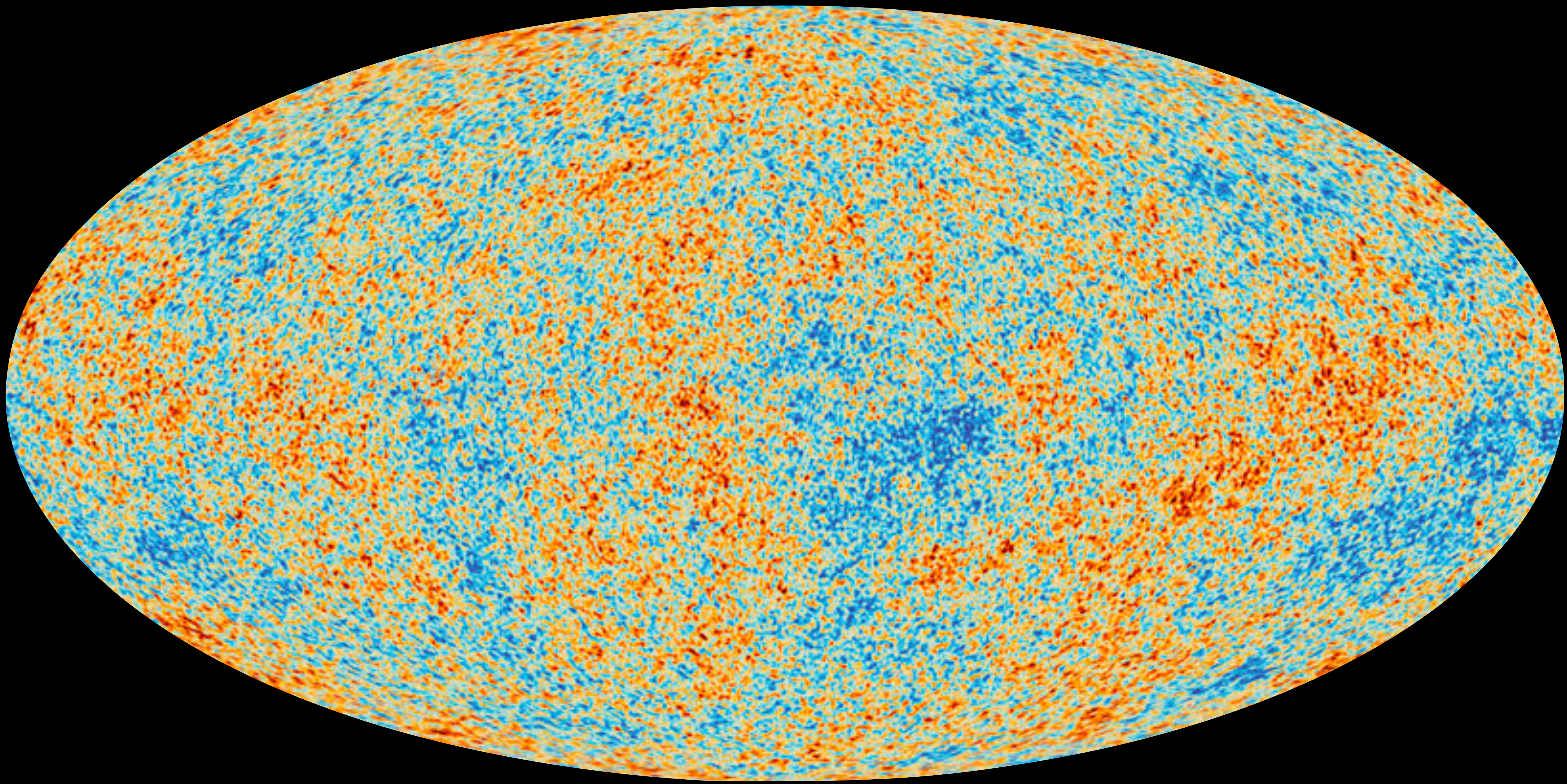
Cosmic Microwave Background: Temperature



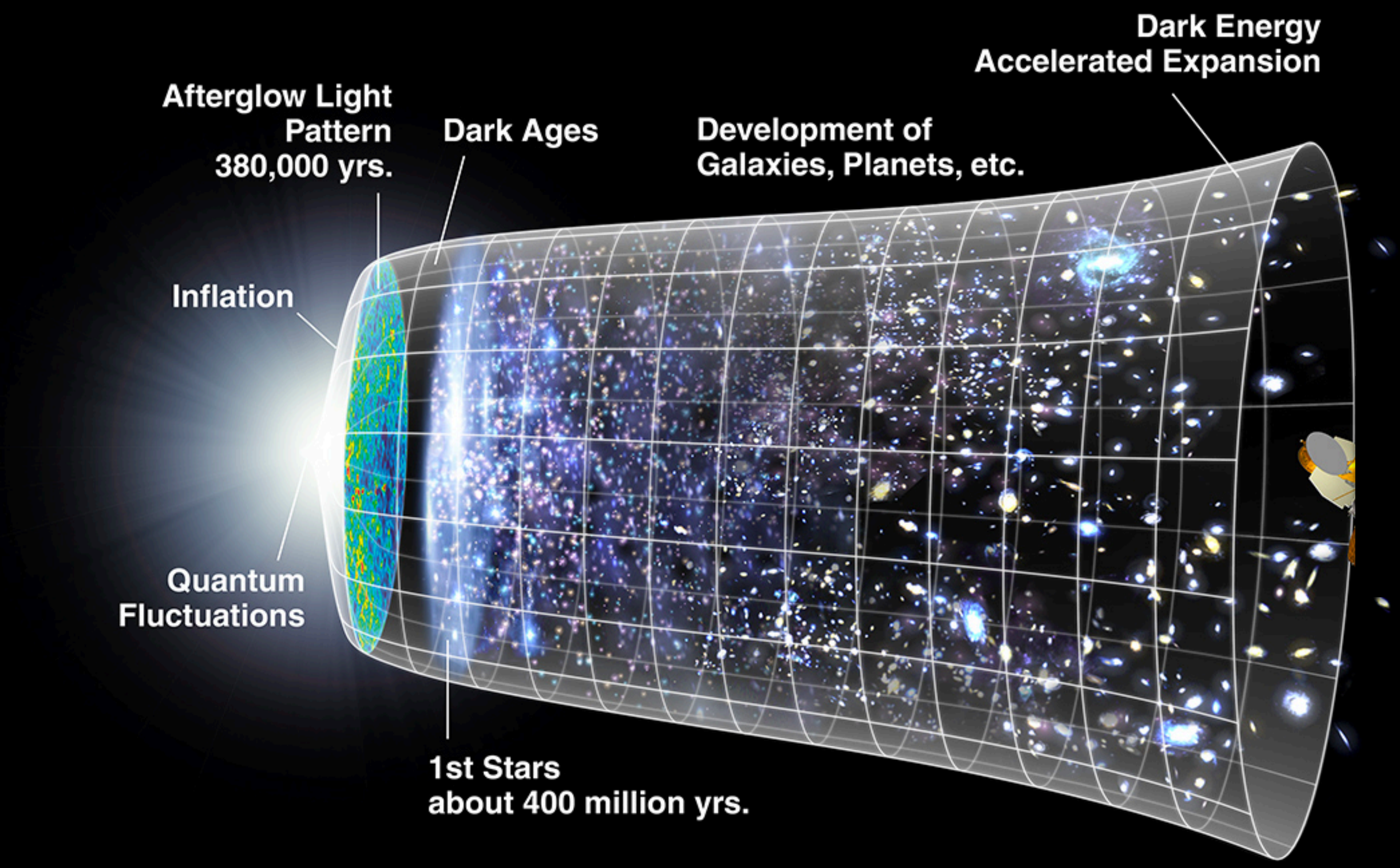


t ~ 400 000 y

Cosmic Microwave Background: Temperature

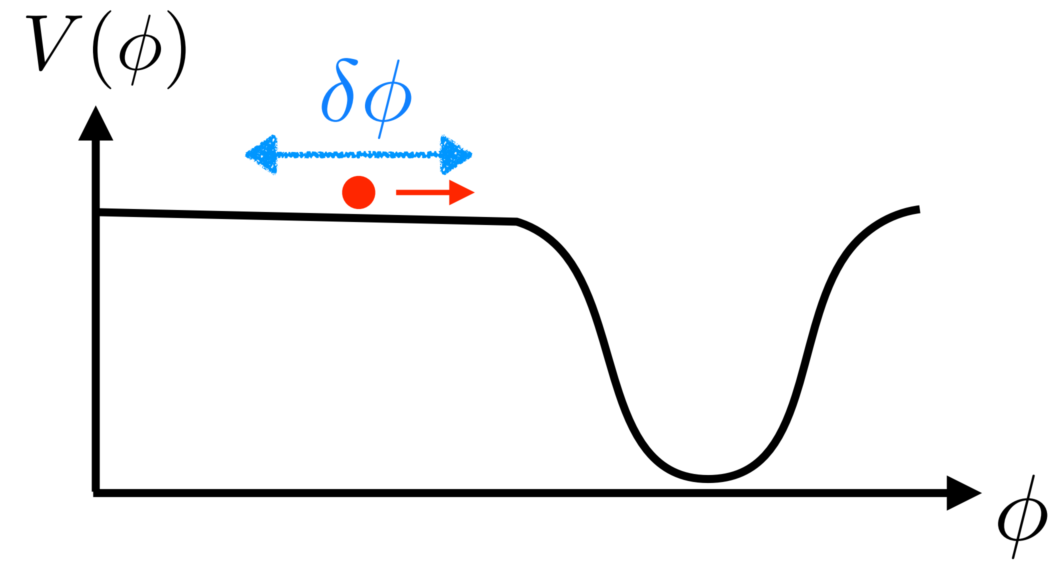


Cosmic inflation

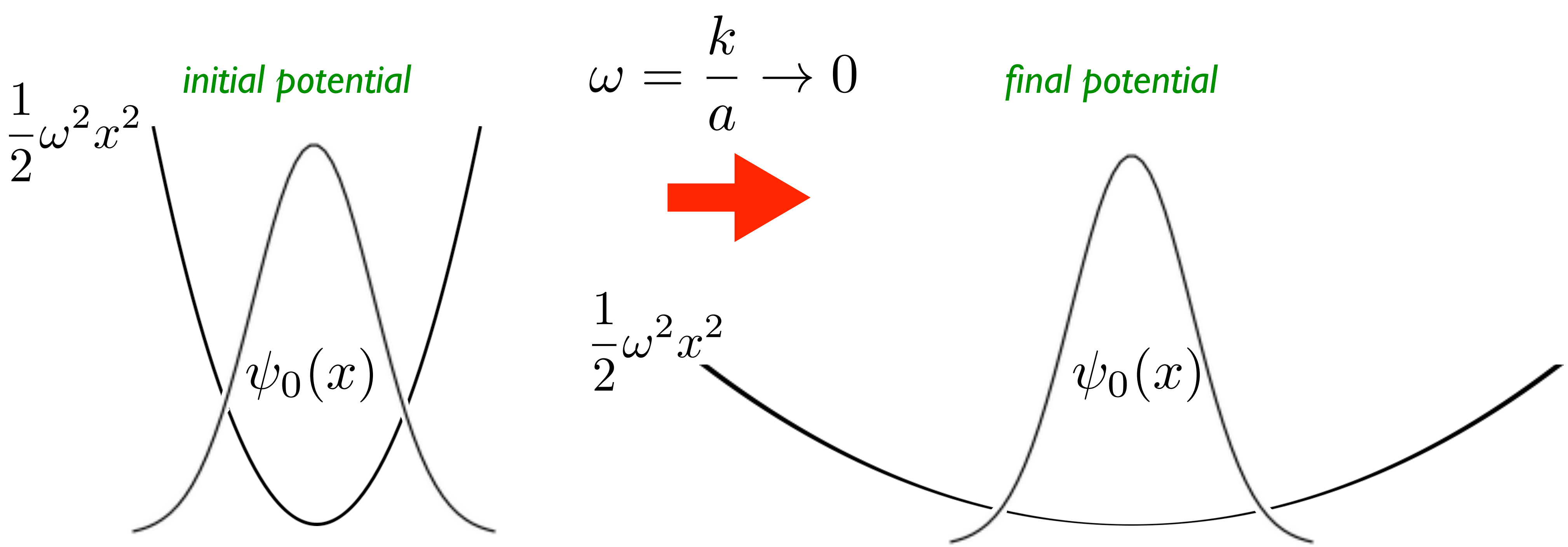


Cosmic inflation

- Inflaton field is homogeneous on average, but has small quantum fluctuations



- Each Fourier mode of these fluctuations behaves as a quantum harmonic oscillator with time dependent spring "constant" because of the expansion

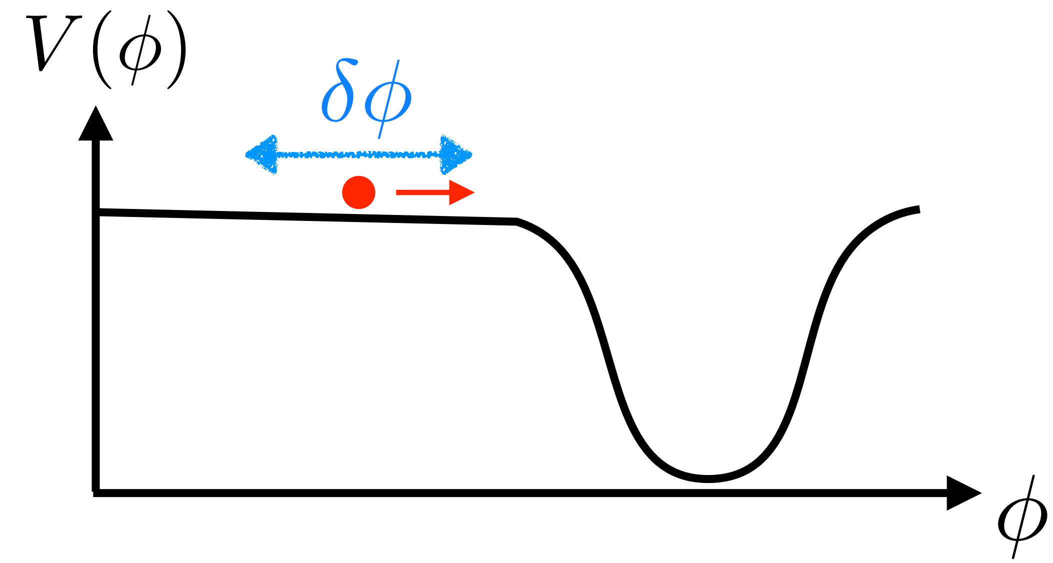


$\omega \gg H$ • High frequency: vacuum I.C.

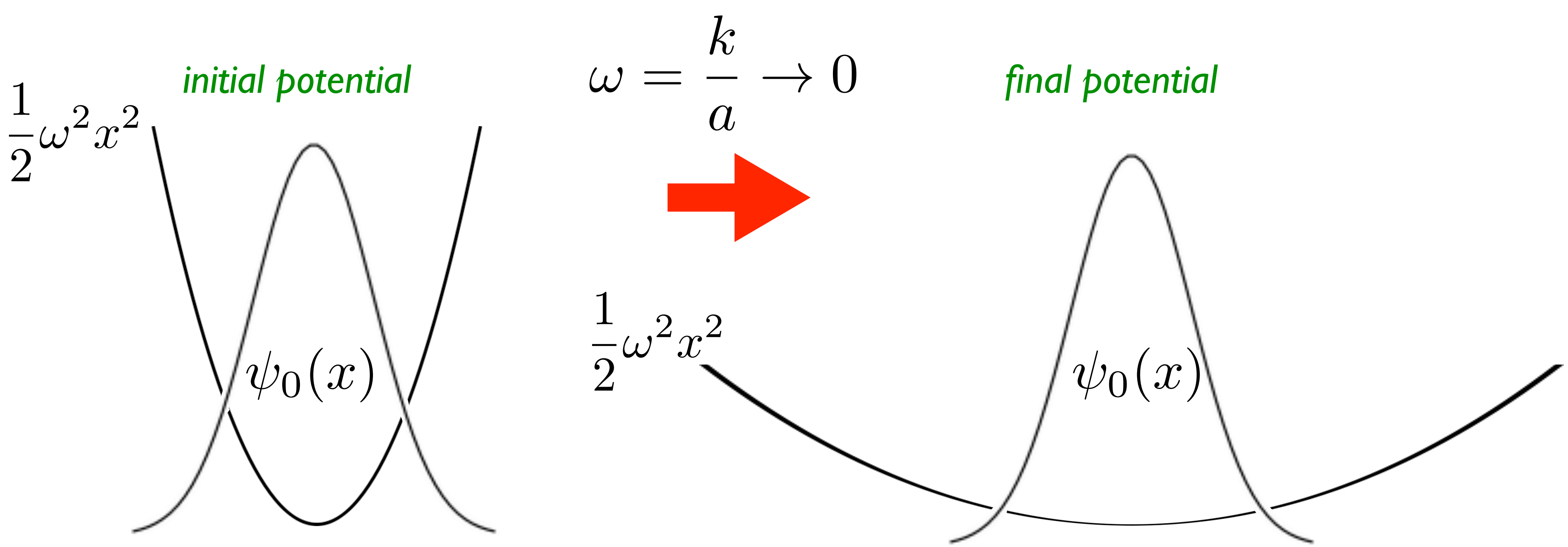
$\omega \ll H$ • Low frequency: fluctuations freeze-in

Cosmic inflation

- Inflaton field is homogeneous on average, but has small quantum fluctuations



- Each Fourier mode of these fluctuations behaves as a quantum harmonic oscillator with time dependent spring "constant" because of the expansion



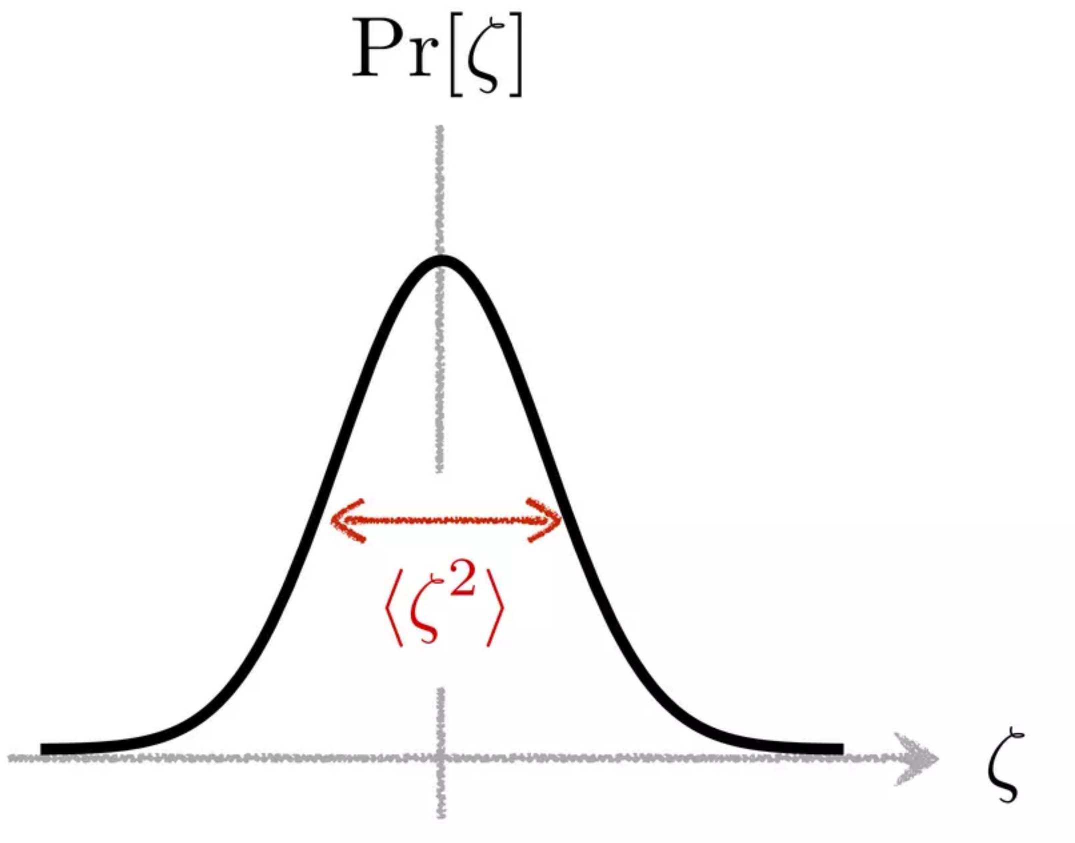
$\omega \gg H$ • High frequency: vacuum I.C.

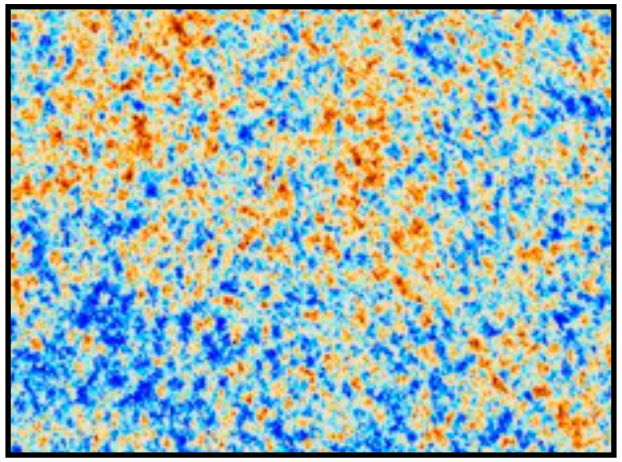
$\omega \ll H$ • Low frequency: fluctuations freeze-in

- Metric perturbations created from inflation: $$g_{ij} = a^2(t) e^{2\zeta(\vec{x})} \delta_{ij}$$

How Gaussian?

- Primordial fluctuations are very Gaussian (as expected from the ground state of harmonic oscillator):



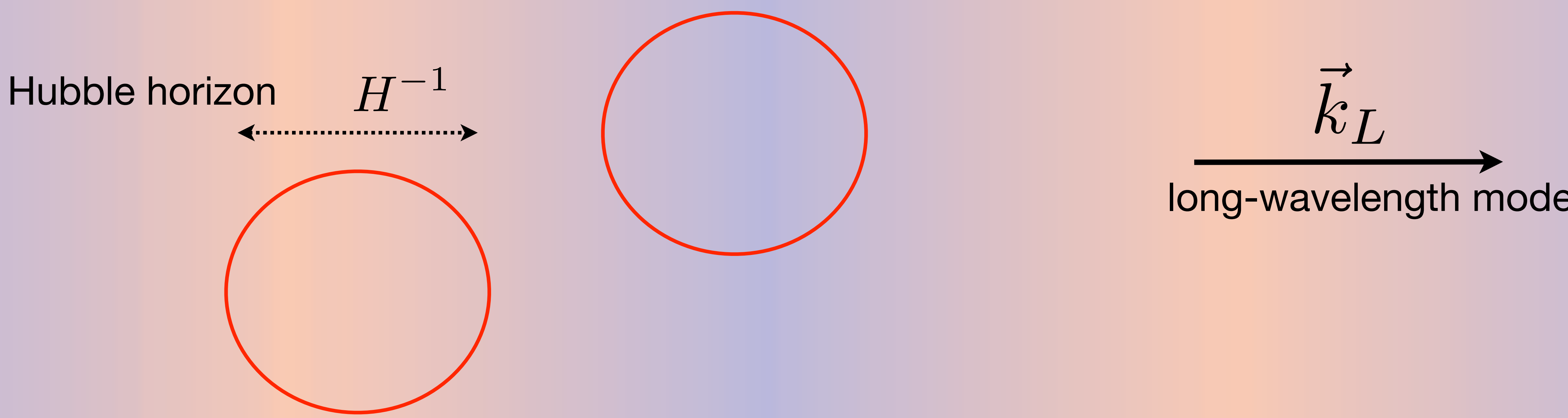


$$\langle\zeta\zeta\zeta\rangle = f_{\mathrm{NL}}\langle\zeta\zeta\rangle^2$$

Three-point function

Small departure from Gaussianity

The long mode



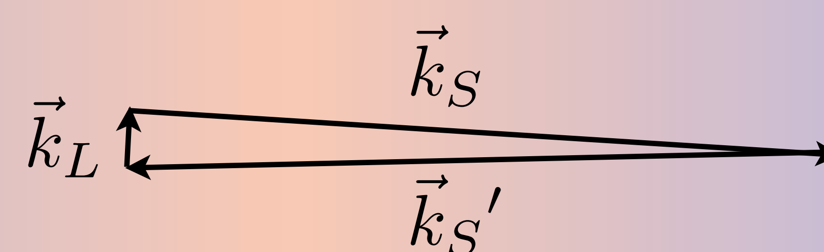
In a universe where everything originates from the same field, a long-wavelength metric perturbation redefines the background = to re-scaling of the coordinates:

$$g_{ij}dx^i dx^j = a^2(t)e^{2\zeta_L(\vec{x})}d\vec{x}^2 = a^2(t)d\tilde{\vec{x}}^2 \quad \Rightarrow \quad \tilde{k} = ke^{-\zeta_L}$$

rescaling of momenta

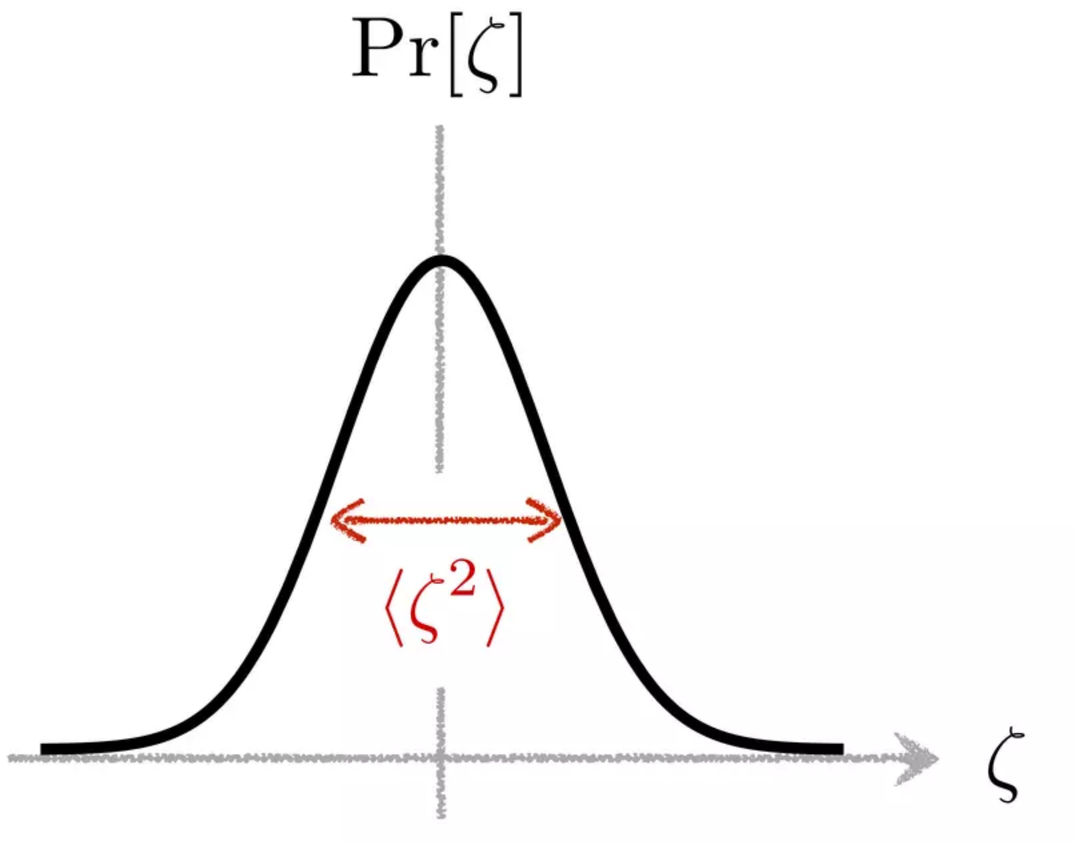
$$\langle \zeta_{\vec{k}_L}\zeta_{\vec{k}_S}\zeta_{\vec{k}'_S}\rangle = \langle \zeta_{\vec{k}_L}\langle \zeta_{\vec{k}_S}\zeta_{\vec{k}_S{}'}\rangle_{\zeta_L}\rangle \approx -\frac{\mathrm{d}\ln\langle \zeta_{\vec{k}_S}\zeta_{-\vec{k}_S}\rangle}{\mathrm{d}\ln k_S}\langle \zeta_{\vec{k}_S}\zeta_{-\vec{k}_S}\rangle\langle \zeta_{\vec{k}_L}\zeta_{-\vec{k}_L}\rangle$$

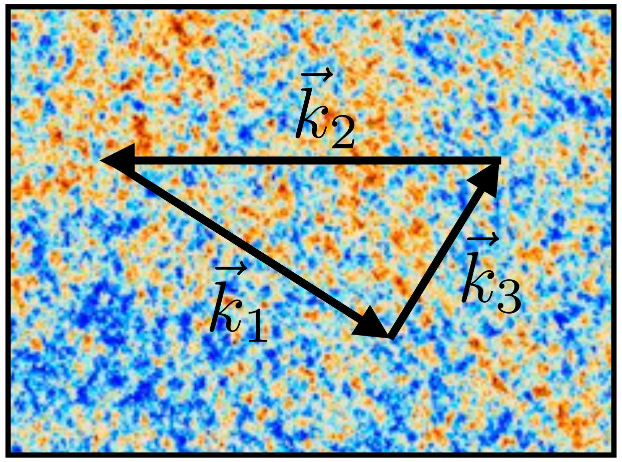
Maldacena ’02



How many fields?

- Primordial fluctuations are very Gaussian (as expected from the ground state of harmonic oscillator):





$$\langle\zeta\zeta\zeta\rangle = f_{\rm NL}\langle\zeta\zeta\rangle^2$$

Three-point function

Small departure from Gaussianity

$$f_{\rm NL} \ll 1$$

- Argument does not apply in multi-field models:

Multi-field models can generically predict larger non-Gaussianity ‘02

$$f_{\rm NL} \gtrsim 1$$

CMB non-Gaussianity

Non-Gaussianity is a discriminant between models

CMB non-Gaussianity

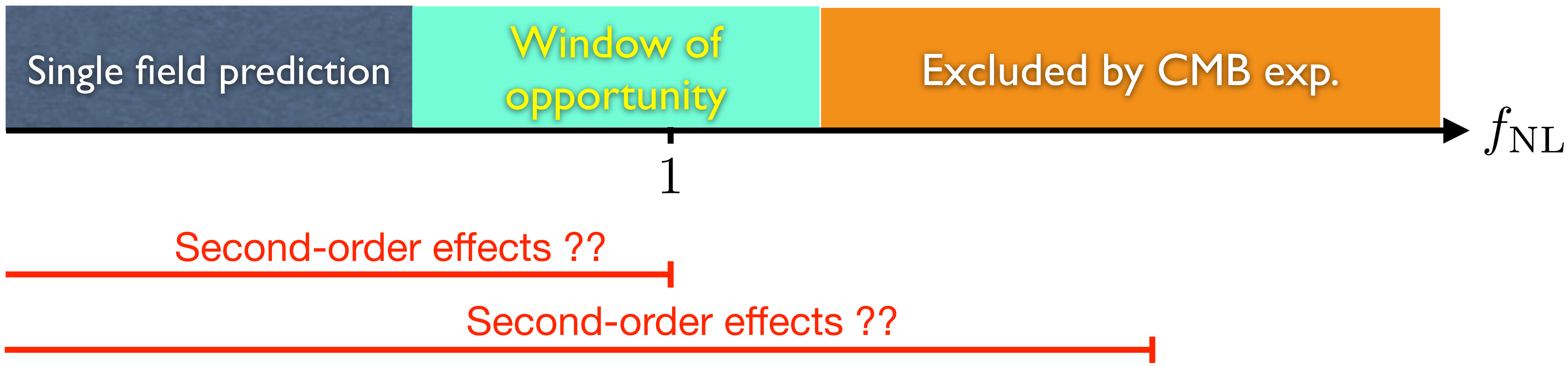
Non-Gaussianity is a discriminant between models

CMB non-Gaussianity

Non-Gaussianity is a discriminant between models

CMB non-Gaussianity

Non-Gaussianity is a discriminant between models

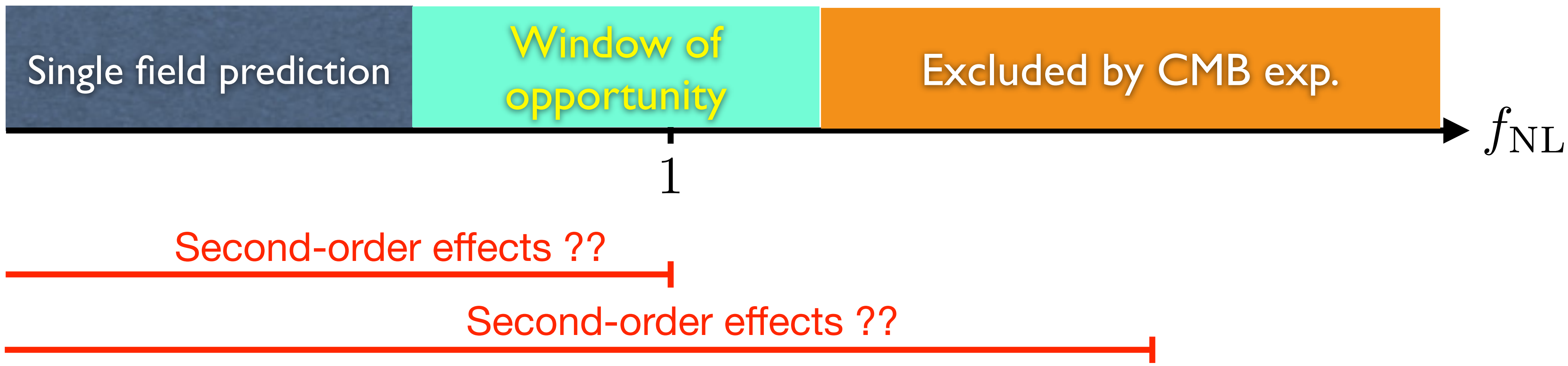


$$\frac{\delta T^{(2)}}{T} \sim \zeta^2 \qquad \Rightarrow \qquad \left\langle \frac{\delta T}{T} \frac{\delta T}{T} \frac{\delta T}{T} \right\rangle \sim \left\langle \frac{\delta T}{T} \frac{\delta T}{T} \right\rangle^2$$

Nonlinearities in the CMB physics (metric and matter perturbations) can induce small non-Gaussian effects. How small?

CMB non-Gaussianity

Non-Gaussianity is a discriminant between models



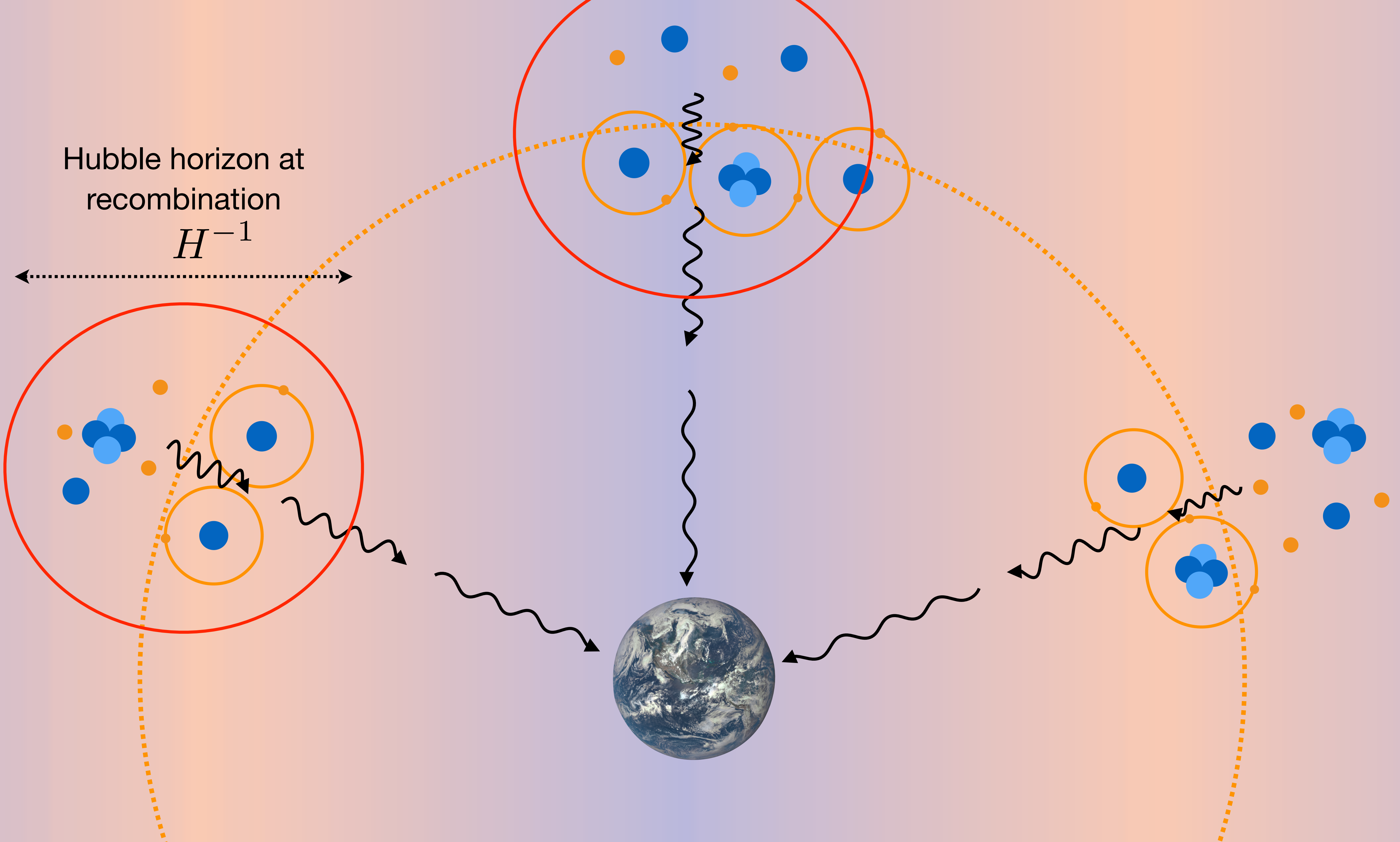
$$\frac{\delta T^{(2)}}{T} \sim \zeta^2 \qquad \Rightarrow \qquad \left\langle \frac{\delta T}{T}\frac{\delta T}{T}\frac{\delta T}{T} \right\rangle \sim \left\langle \frac{\delta T}{T}\frac{\delta T}{T} \right\rangle^2$$

Nonlinearities in the CMB physics (metric and matter perturbations) can induce small non-Gaussian effects. How small?

- Solving coupled Boltzmann and Einstein equations up to 2nd order '08:

$$\frac{df_I}{d\eta} = C_I[f_I]\ , \quad I = \gamma, \nu, b, {\rm CDM} \qquad \& \qquad G_{ij} = 8\pi G \sum_I T_{ij}^{(I)}$$

Integration of the photon temperature along the line of sight

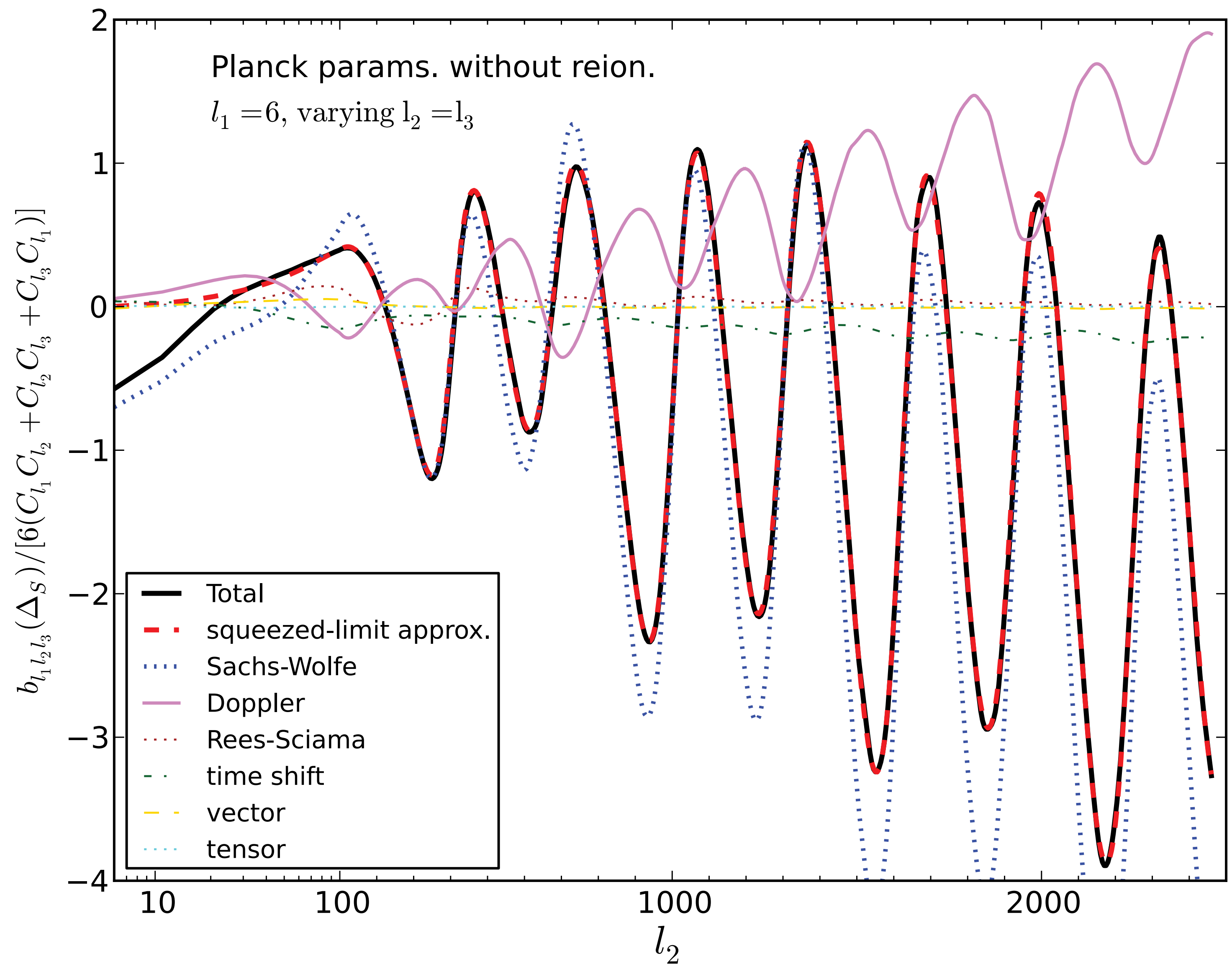


$$b_{l_1 l_2 l_3} = C_{l_1}C_{l_2} + C_{l_1}C_{l_3} + C_{l_2}C_{l_3} - \frac{1}{2}C^{T\zeta}_{l_1}\left(C_{l_2}\frac{d\ln(l_2^2 C_{l_2})}{d\ln l_2} + C_{l_3}\frac{d\ln(l_3^2 C_{l_3})}{d\ln l_3}\right)$$

$$l_1 \ll l_2, l_3$$

This relation can be used to test the consistency of Einstein-Boltzmann codes ‘11

Agreement between full calculation and analytic expression '12



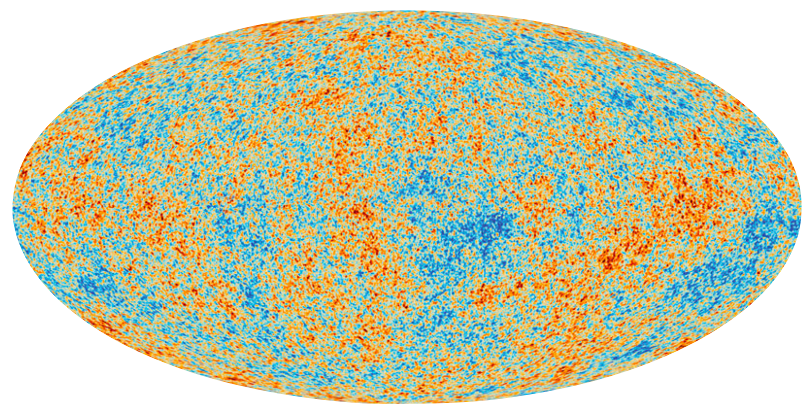
$$b_{l_1 l_2 l_3} = C_{l_1}C_{l_2} + C_{l_1}C_{l_3} + C_{l_2}C_{l_3} - \frac{1}{2}C^{T\zeta}_{l_1}\left(C_{l_2}\frac{d\ln(l_2^2 C_{l_2})}{d\ln l_2} + C_{l_3}\frac{d\ln(l_3^2 C_{l_3})}{d\ln l_3}\right)$$

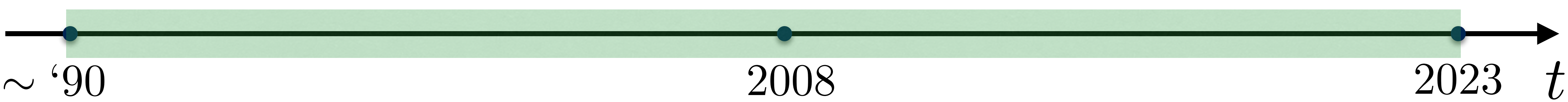
$$l_1 \ll l_2, l_3$$

This relation can be used to test the consistency of Einstein-Boltzmann codes

Cosmic Microwave Background:

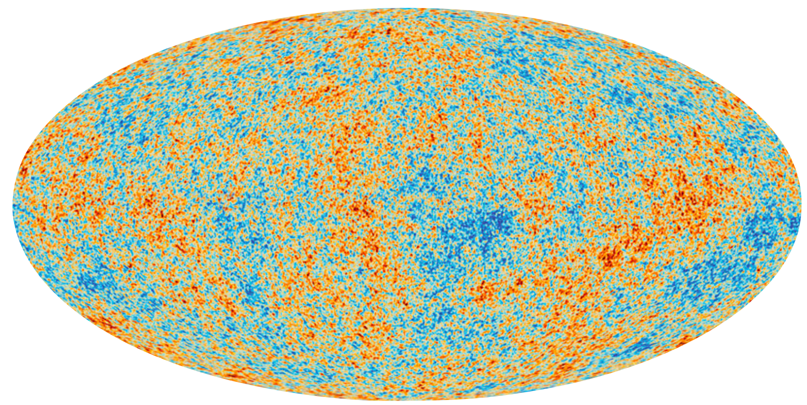
WMAP 2001-10,
Planck 2010-15, …

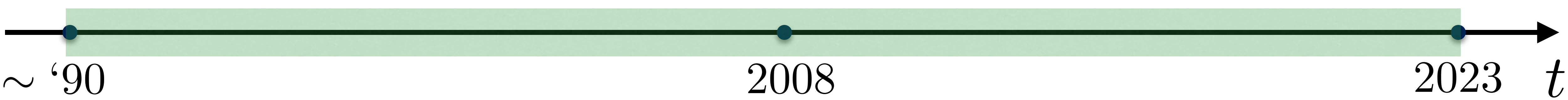




Cosmic Microwave Background:

WMAP 2001-10,
Planck 2010-15, …

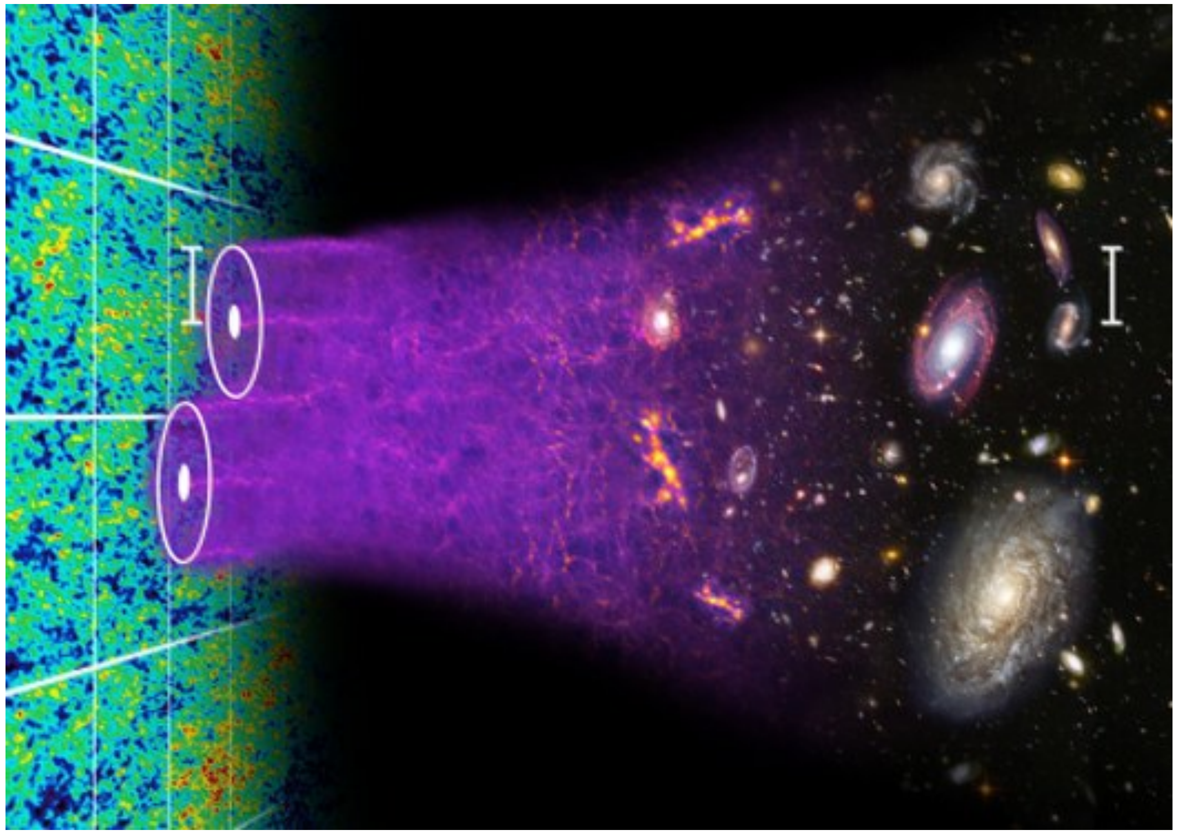


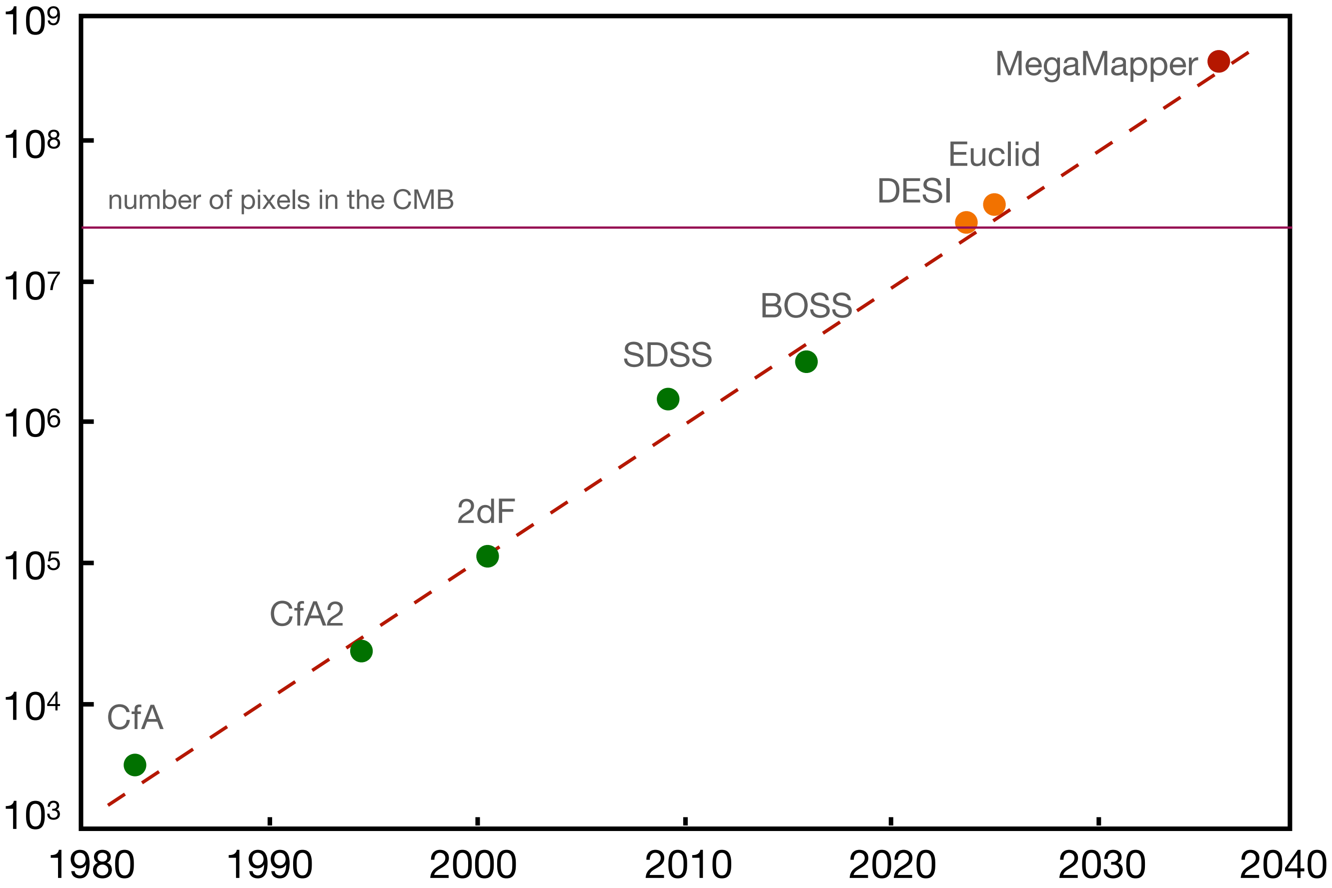


Large-scale structure

Large-scale structure

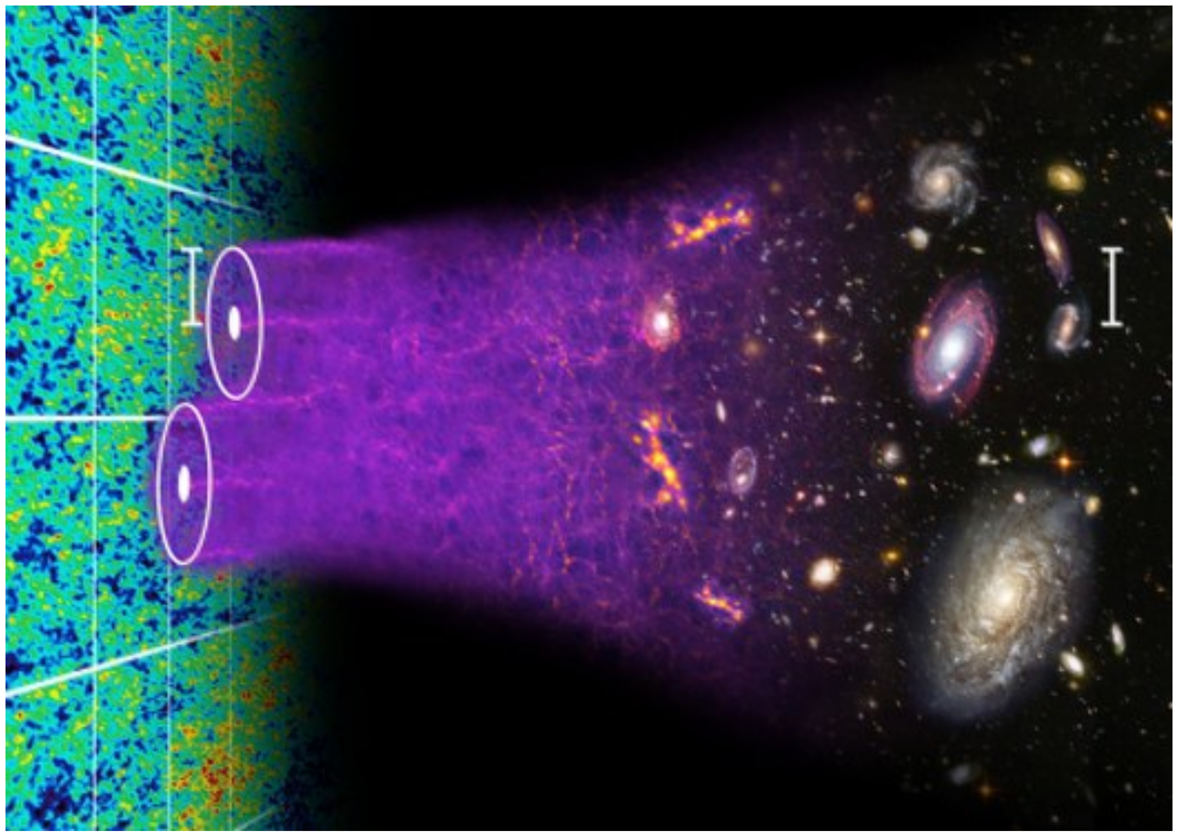
- Forthcoming LSS surveys will contain many more modes than the CMB

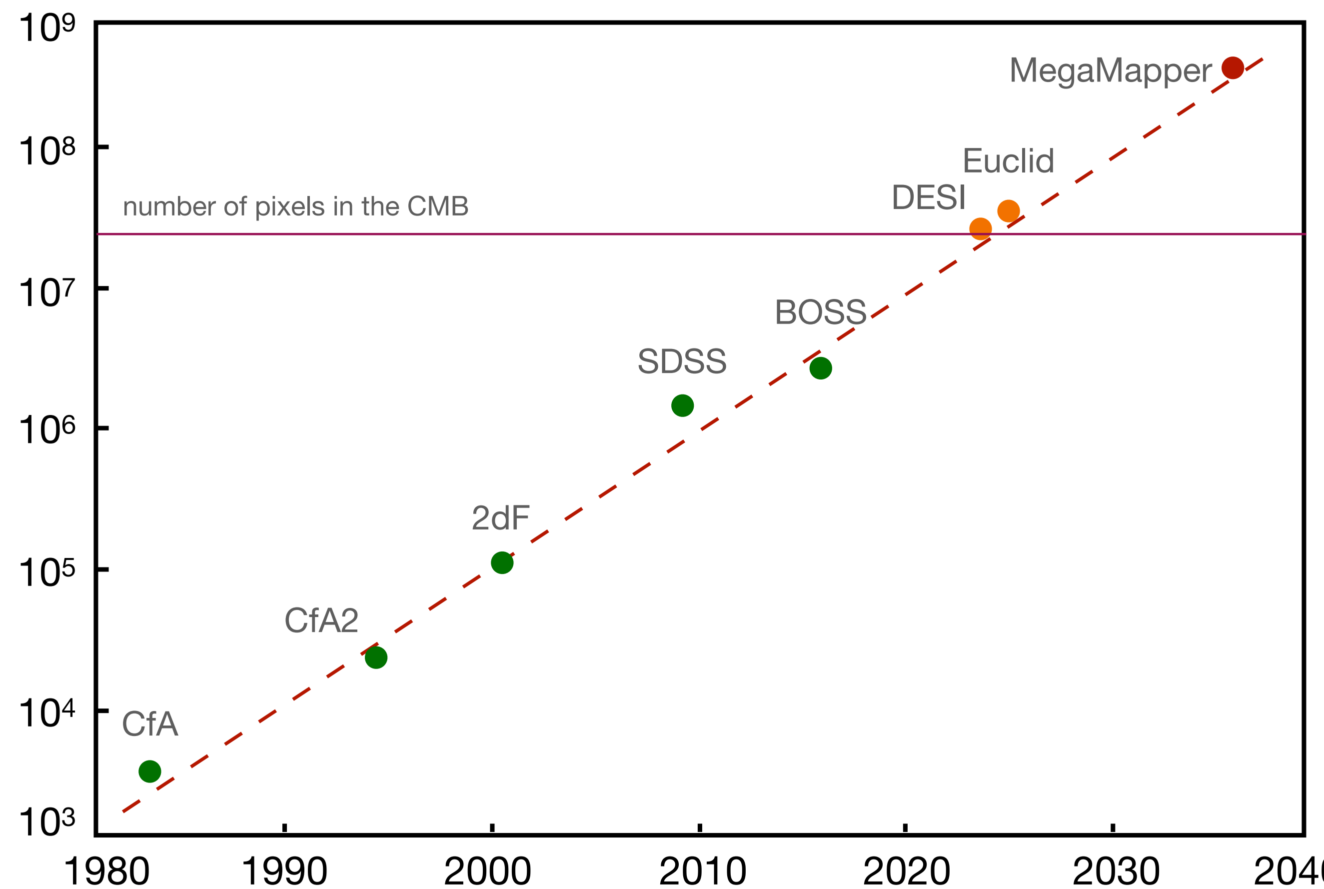




Large-scale structure

- Forthcoming LSS surveys will contain many more modes than the CMB



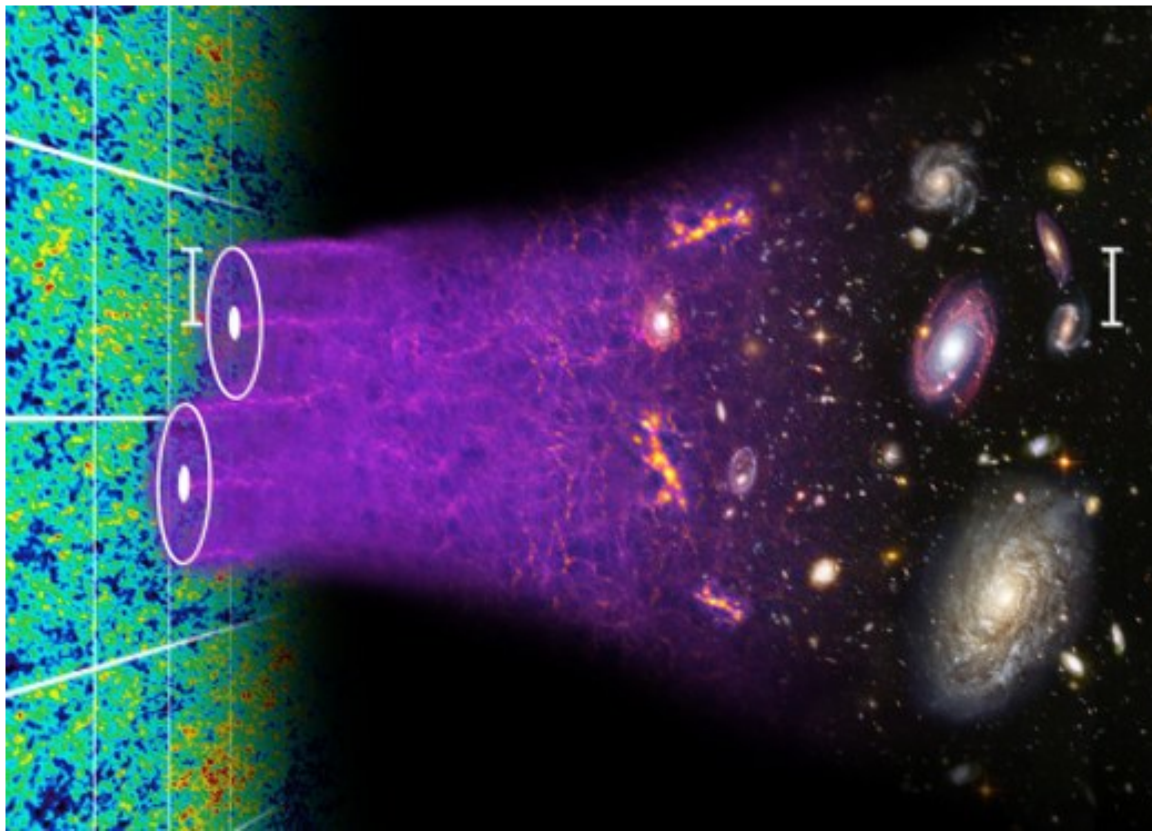


- Improve our understanding on initial conditions $$\Delta f_{\rm NL} \sim \frac{10^4}{N_{\rm modes}^{1/2}}$$

- Improve our understanding of the energy content of the Universe and of the gravitational sector.

Large-scale structure

- Forthcoming LSS surveys will contain many more modes than the CMB

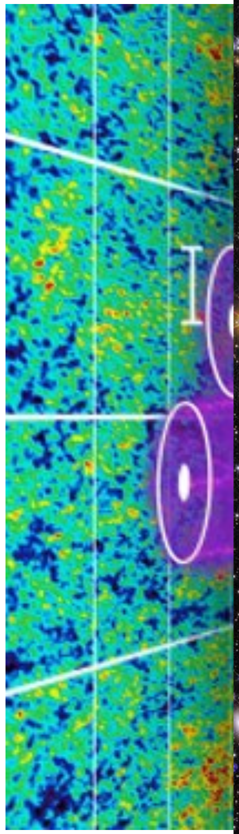


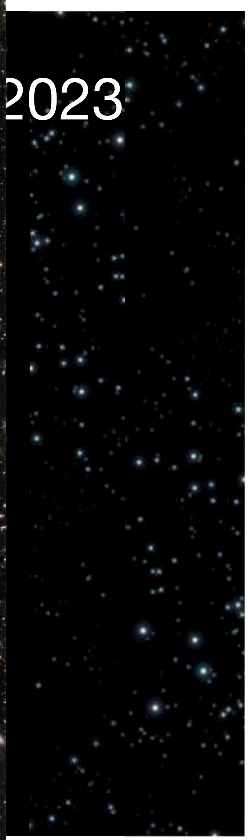
- Improve our understanding on initial conditions $\Delta f_{\rm NL} \sim \dfrac{10^4}{N_{\rm modes}^{1/2}}$

- Improve our understanding of the energy content of the Universe and of the gravitational sector.

Larg

• Forth



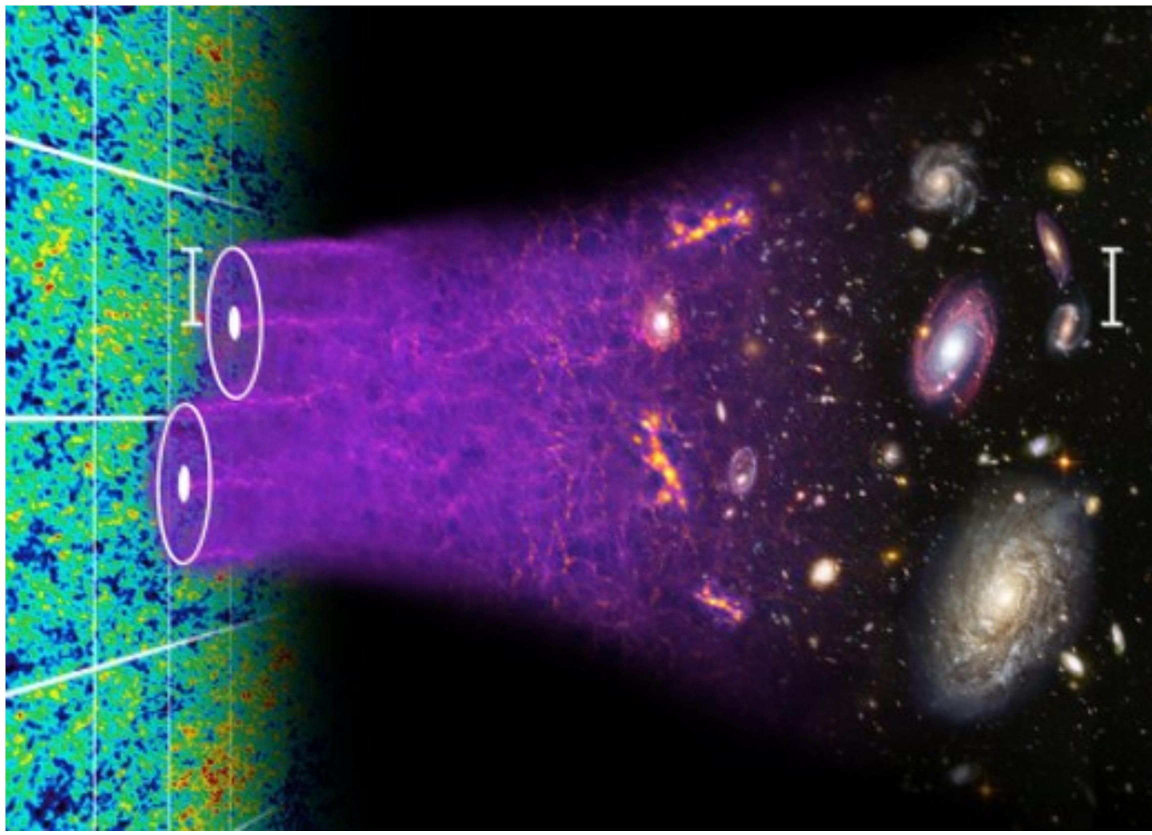


• Impro

• Impro tational sector.

Large-scale structure

- Forthcoming LSS surveys will contain many more modes than the CMB



- Improve our understanding on initial conditions

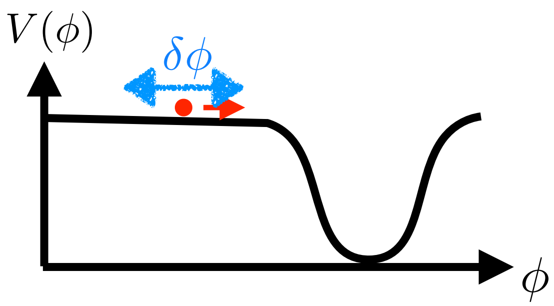
$$\Delta f_{\rm NL} \sim \frac{10^4}{N_{\rm modes}^{1/2}}$$

- Improve our understanding of the energy content of the Universe and of the gravitational sector.

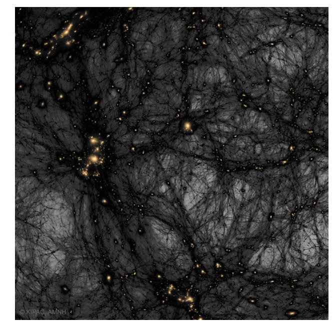
- Challenges: nonlinearities, baryonic physics, bias, galaxy formation and merging, etc… Much more difficult than CMB.

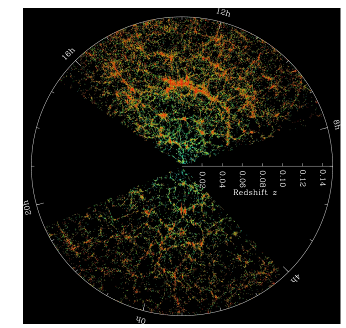
Precision tests with the LSS

- Modelling the observables (galaxy clustering, gravitational lensing, etc.) on linear and nonlinear scales with high accuracy (long and strong tradition at IPhT)



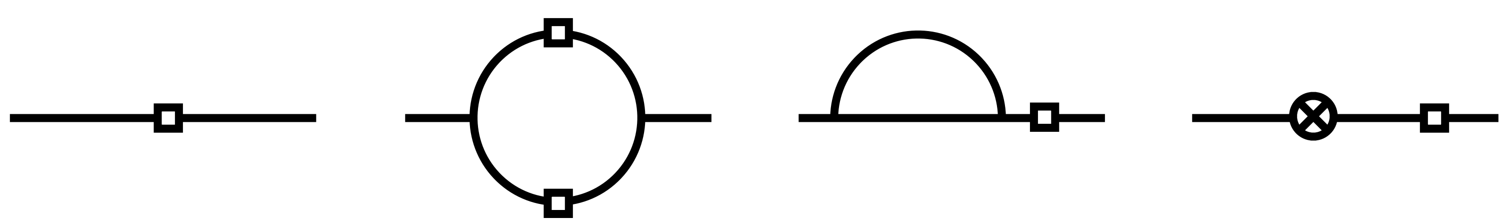
Initial Conditions





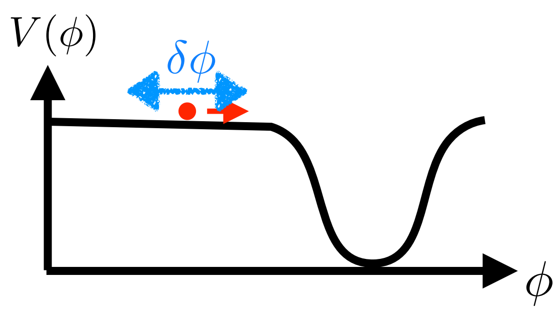
Large-Scale Structure

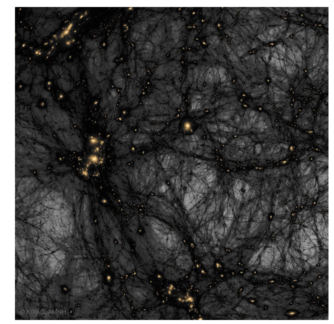
$\zeta(\boldsymbol{x}, 0)$ —SPT, EFT-of-LSS / N-body simulations→ $\delta(\boldsymbol{x}, \tau)$ dark matter —RSD→ $\delta_g(\theta, z)$ galaxies

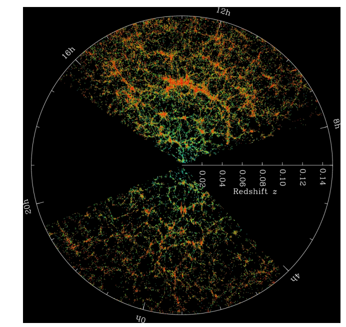


Precision tests with the LSS

- Modelling the observables (galaxy clustering, gravitational lensing, etc.) on linear and nonlinear scales with high accuracy (long and strong tradition at IPhT)







Initial Conditions

Large-Scale Structure

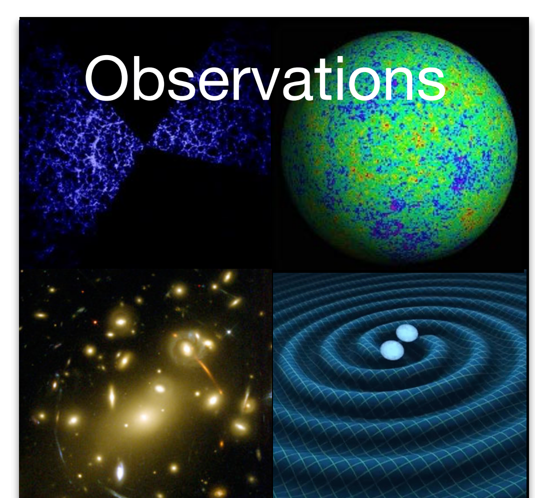
$\zeta(\boldsymbol{x}, 0)$ —SPT, EFT-of-LSS / N-body simulations→ $\delta(\boldsymbol{x}, \tau)$ dark matter —RSD→ $\delta_g(\theta, z)$ galaxies

- Exploring theory space and modelling the phenomenology of new physics on cosmological scales (long and strong tradition at IPhT)

Gravitational theories

$$
\begin{aligned}
&G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \\
&- 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right] \\
&+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X) \\
&\times \left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right] \\
&+ \ldots
\end{aligned}
$$

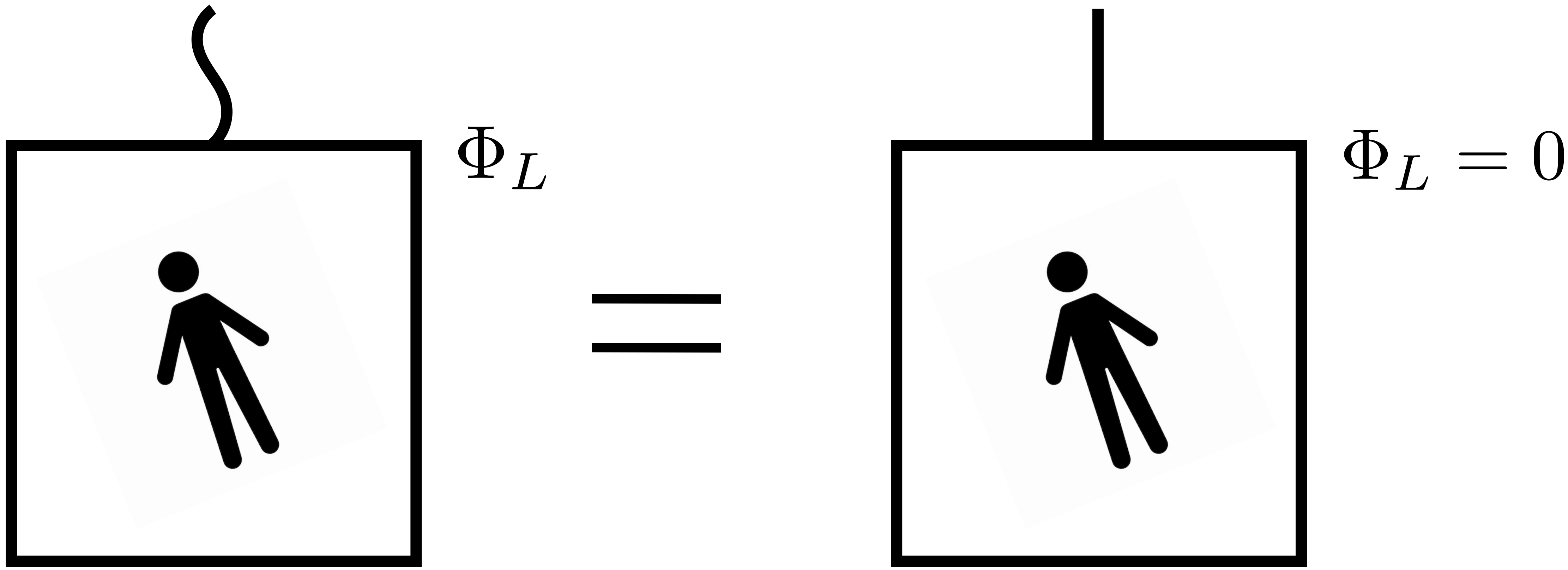
⟷



The long mode, again

Locally, a gravitational field is indistinguishable from an acceleration (Equivalence Principle)

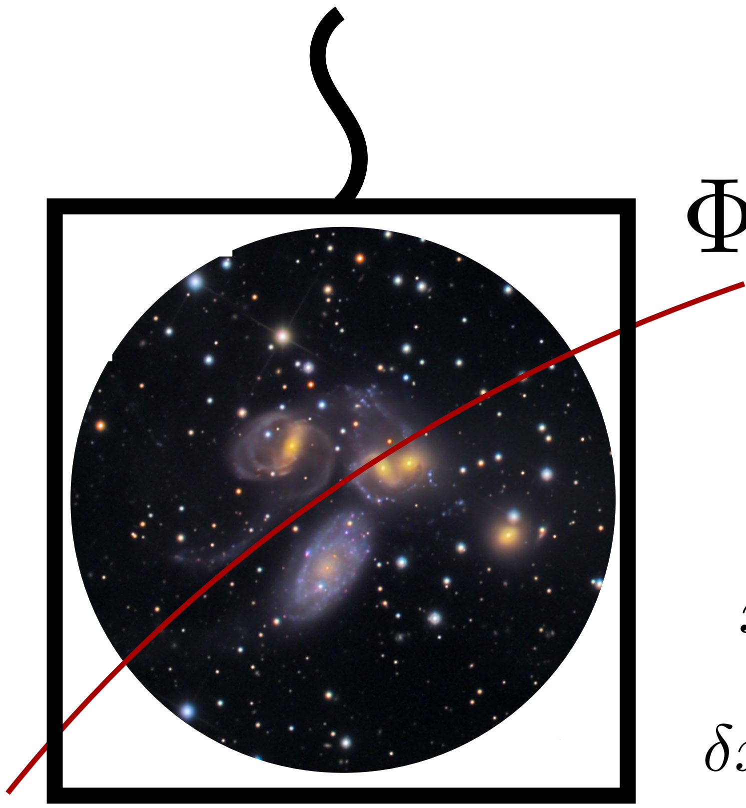
$$\Phi_L(\vec{x}) = \Phi_L(\vec{0}) + x^i \nabla_i \Phi(\vec{0}) + \ldots$$



Consistency relations of the LSS

Locally, a gravitational field is indistinguishable from an acceleration (Equivalence Principle)

$$\Phi_L(\vec{x}) = \Phi_L(\vec{0}) + x^i \nabla_i \Phi(\vec{0}) + \ldots$$



Φ_L

$=$

$$x^i \to x^i + \delta x^i$$

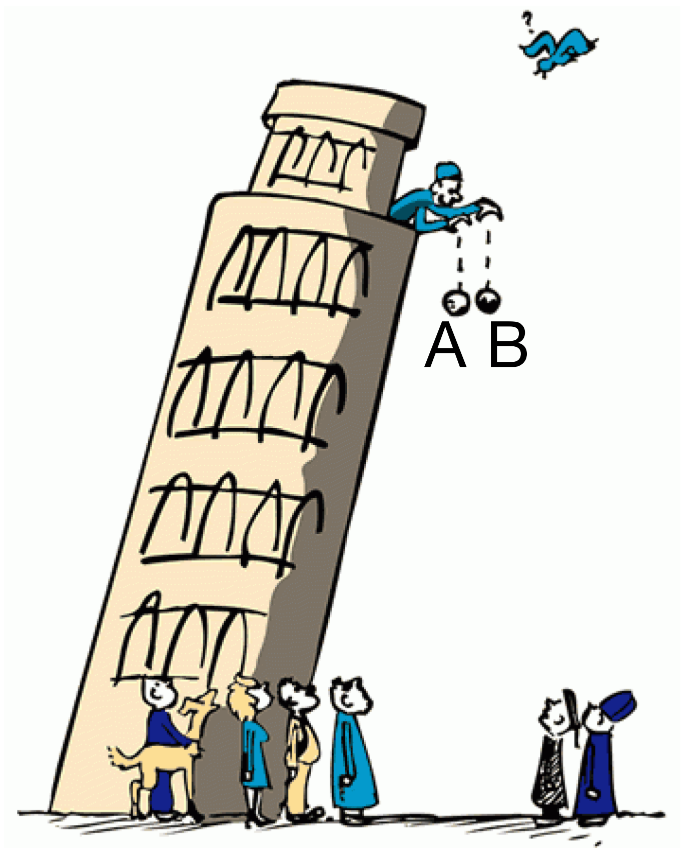
$$\delta x^i = -\int v^i(\eta) d\eta$$

$\Phi_L = 0$

$$\langle \delta_{\vec{k}_L}(t)\delta_{\vec{k}_1}(t_1)\delta_{\vec{k}_2}(t_2)\rangle' \simeq \langle \delta_{\vec{k}_L}(t)\delta_{-\vec{k}_L}(t)\rangle' \frac{\vec{k}_L \cdot \vec{k}_1}{k_L^2} \left[\frac{D(t_1)}{D(t)} \langle \delta_{\vec{k}_1}(t_1)\delta_{-\vec{k}_1}(t_1)\rangle' - \frac{D(t_2)}{D(t)} \langle \delta_{\vec{k}_2}(t_2)\delta_{-\vec{k}_2}(t_2)\rangle' \right]$$

Valid for any tracers, hold nonlinearly in the short modes, after shell crossing, including baryonic physics and bias '13 — '17

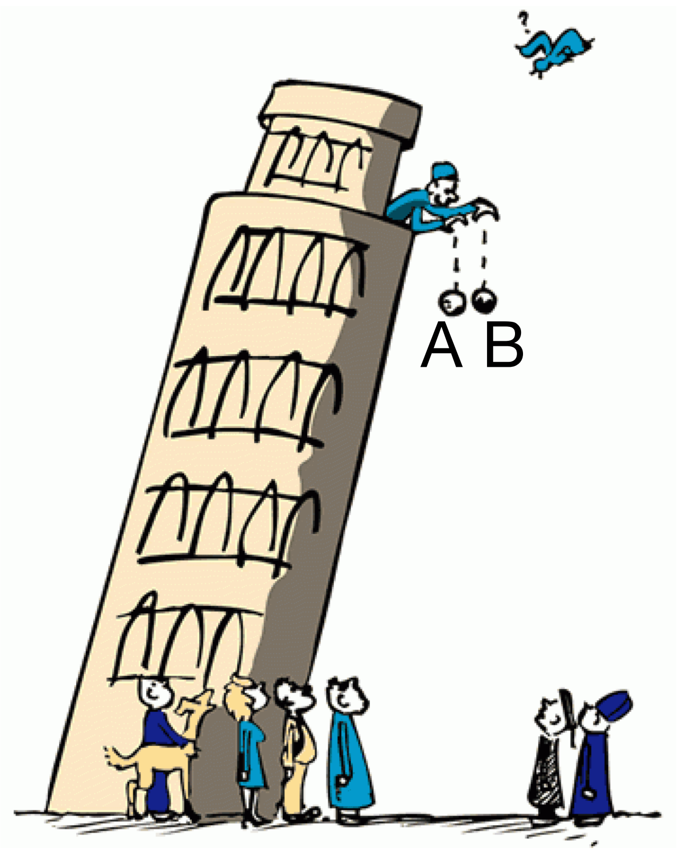
Test of the Equivalence Principle



The Equivalence Principle is very well tested on small scales.

One must wait a few seconds until two objects touch the ground.

Test of the Equivalence Principle



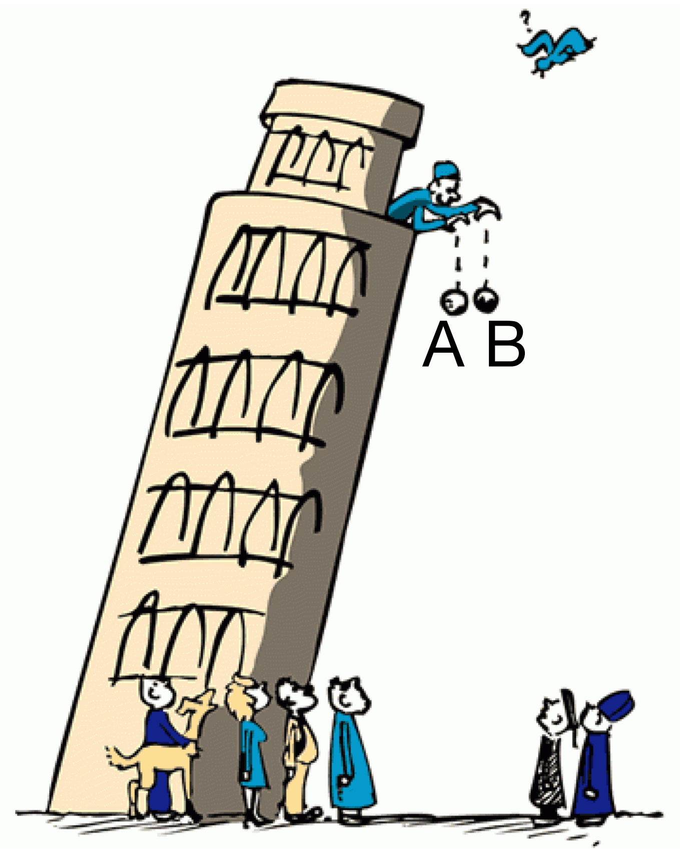
The Equivalence Principle is very well tested on small scales.
One must wait a few seconds until two objects touch the ground.

For galaxies, the waiting time is the age of the universe…

$$\langle \delta_{\vec{k}_L}(t) \delta^A_{\vec{k}_1}(t) \delta^B_{\vec{k}_2}(t) \rangle' \simeq 0$$

if Equivalence Principle holds

Test of the Equivalence Principle



The Equivalence Principle is very well tested on small scales.
One must wait a few seconds until two objects touch the ground.

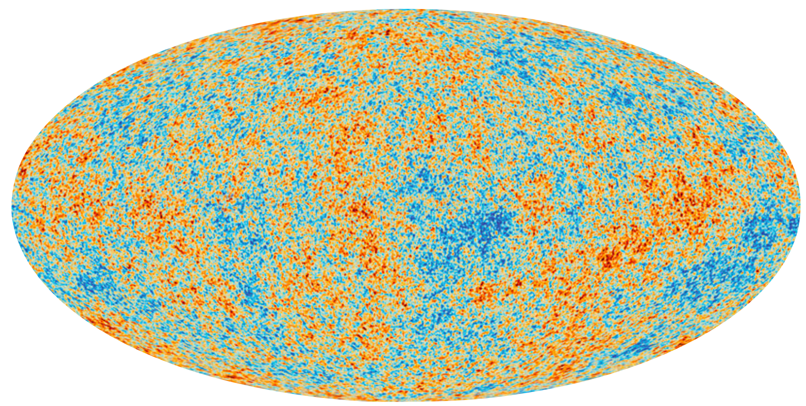
For galaxies, the waiting time is the age of the universe…

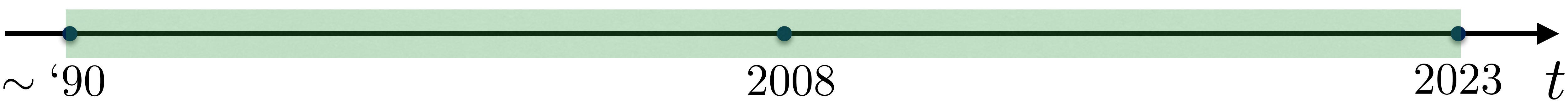
$$\langle \delta_{\vec{k}_L}(t)\delta^A_{\vec{k}_1}(t)\delta^B_{\vec{k}_2}(t)\rangle' \simeq \epsilon \langle \delta_{\vec{k}_L}(t)\delta_{-\vec{k}_L}(t)\rangle' \frac{\vec{k}_L\cdot\vec{k}}{k_L^2}\langle \delta^A_{\vec{k}}(t)\delta^B_{-\vec{k}}(t)\rangle'$$

if Equivalence Principle is violated ‘13

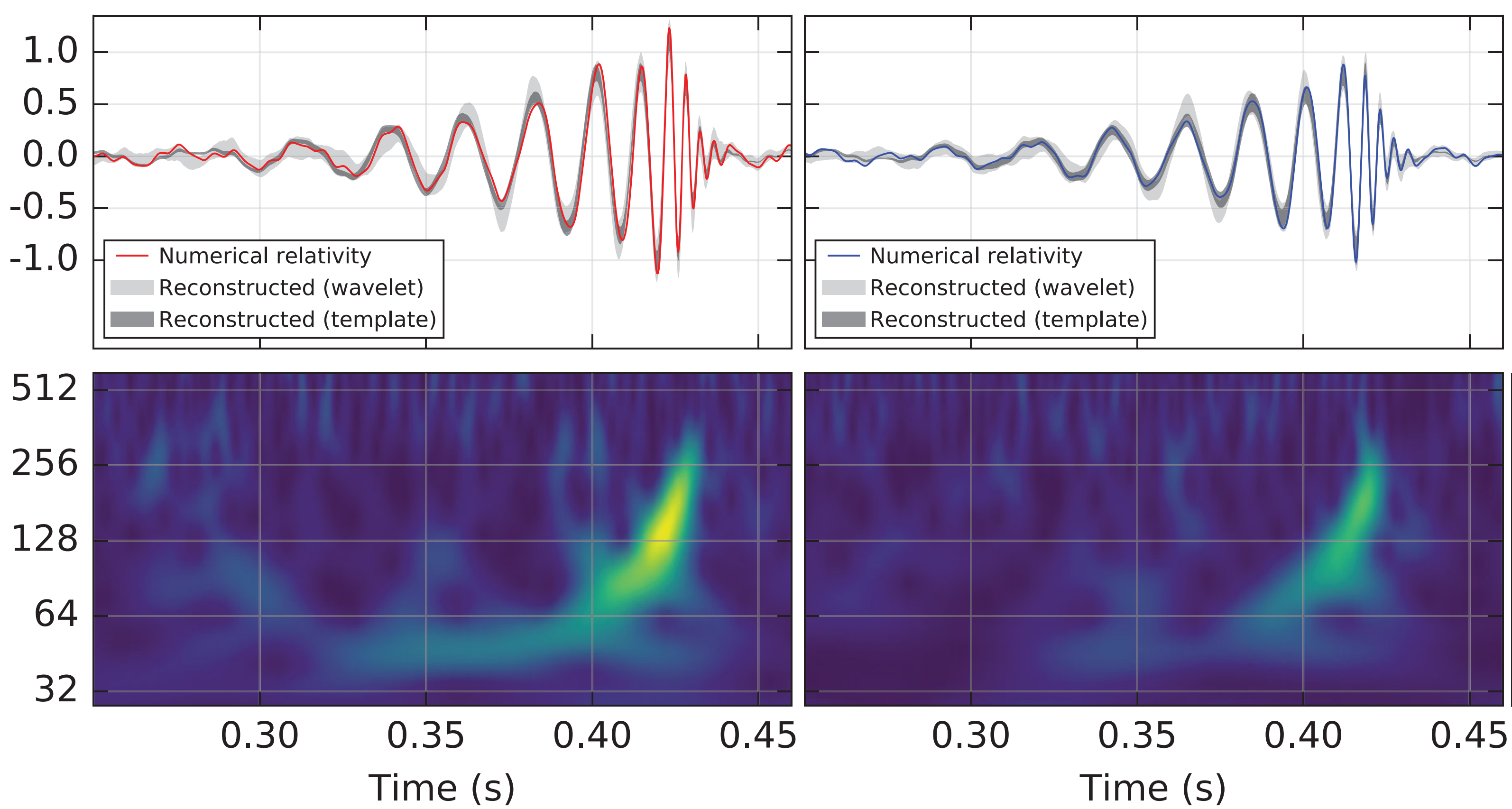
Cosmic Microwave Background:

WMAP 2001-10,
Planck 2010-15, …

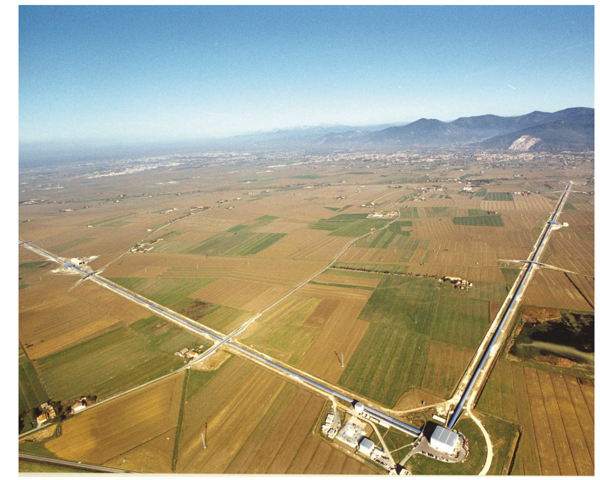


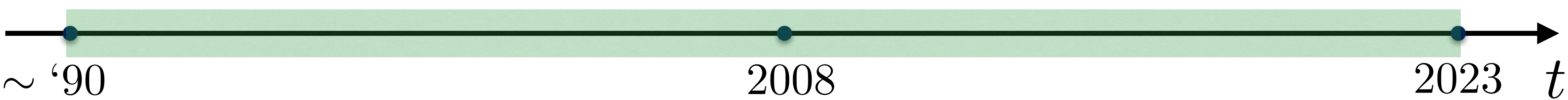


Large-scale structure

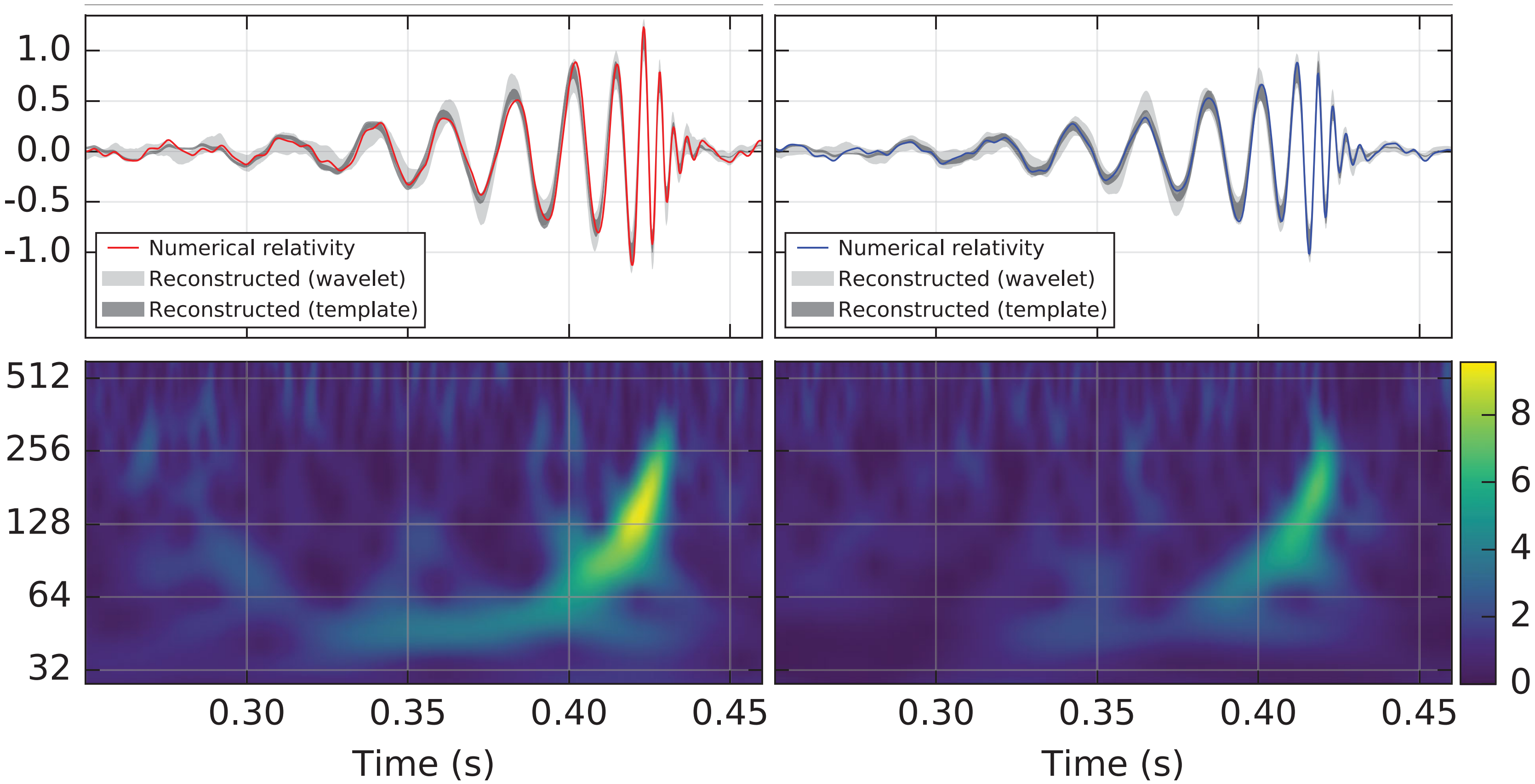


Gravitational waves

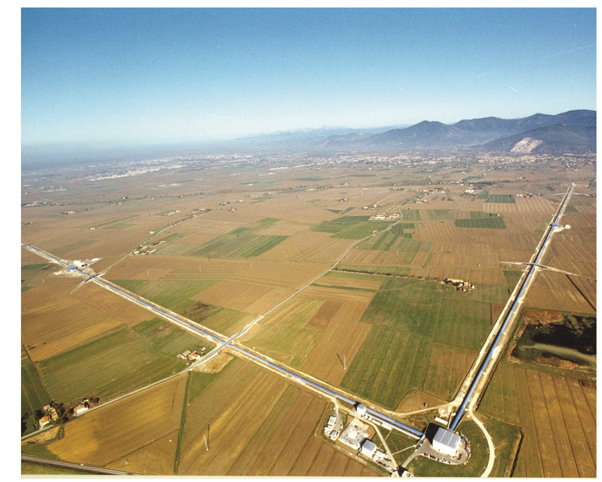


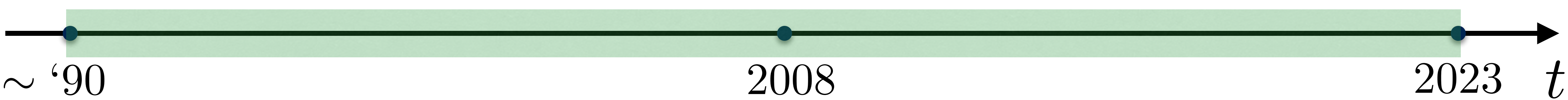


Large-scale structure

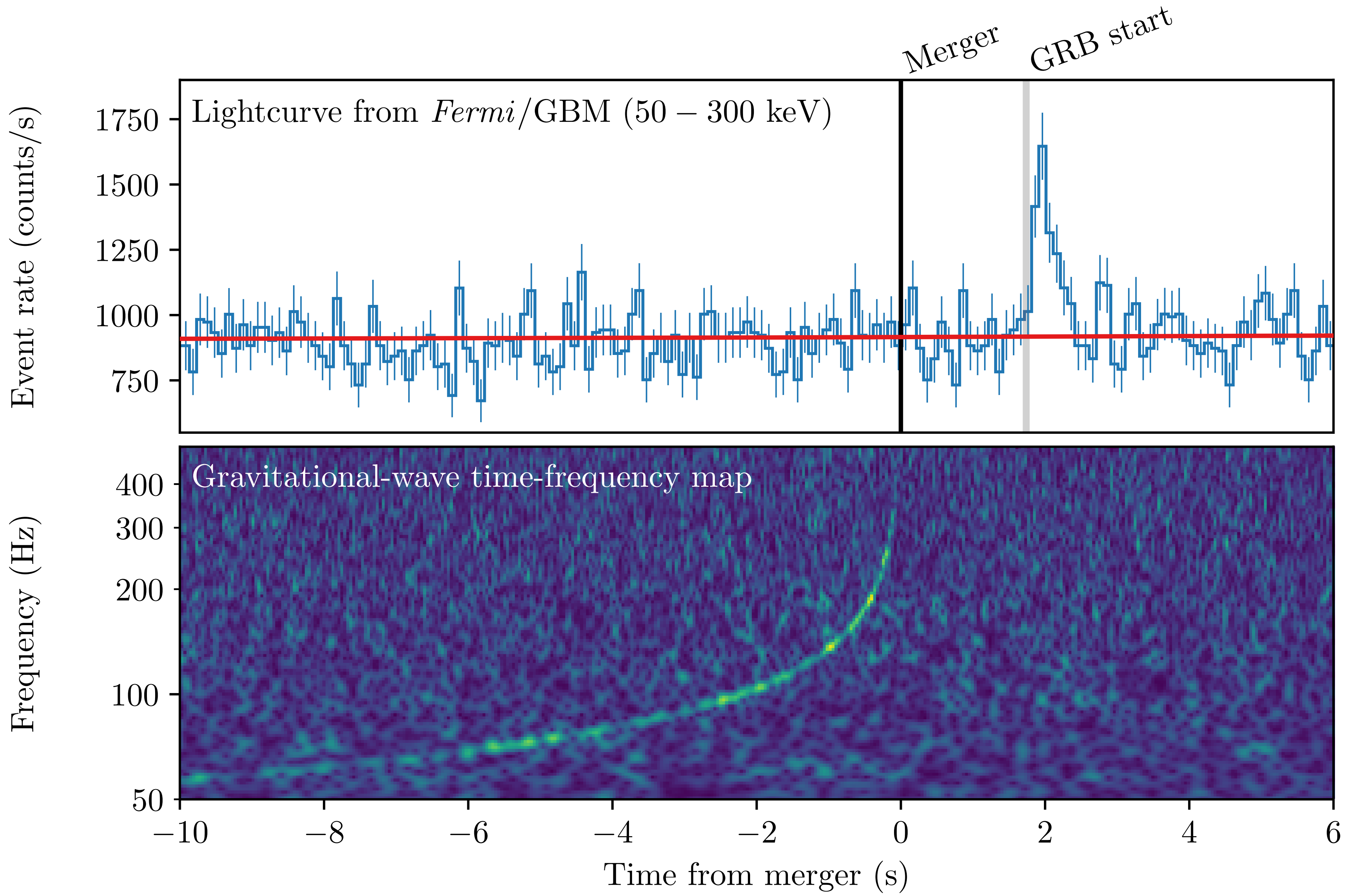


Gravitational waves





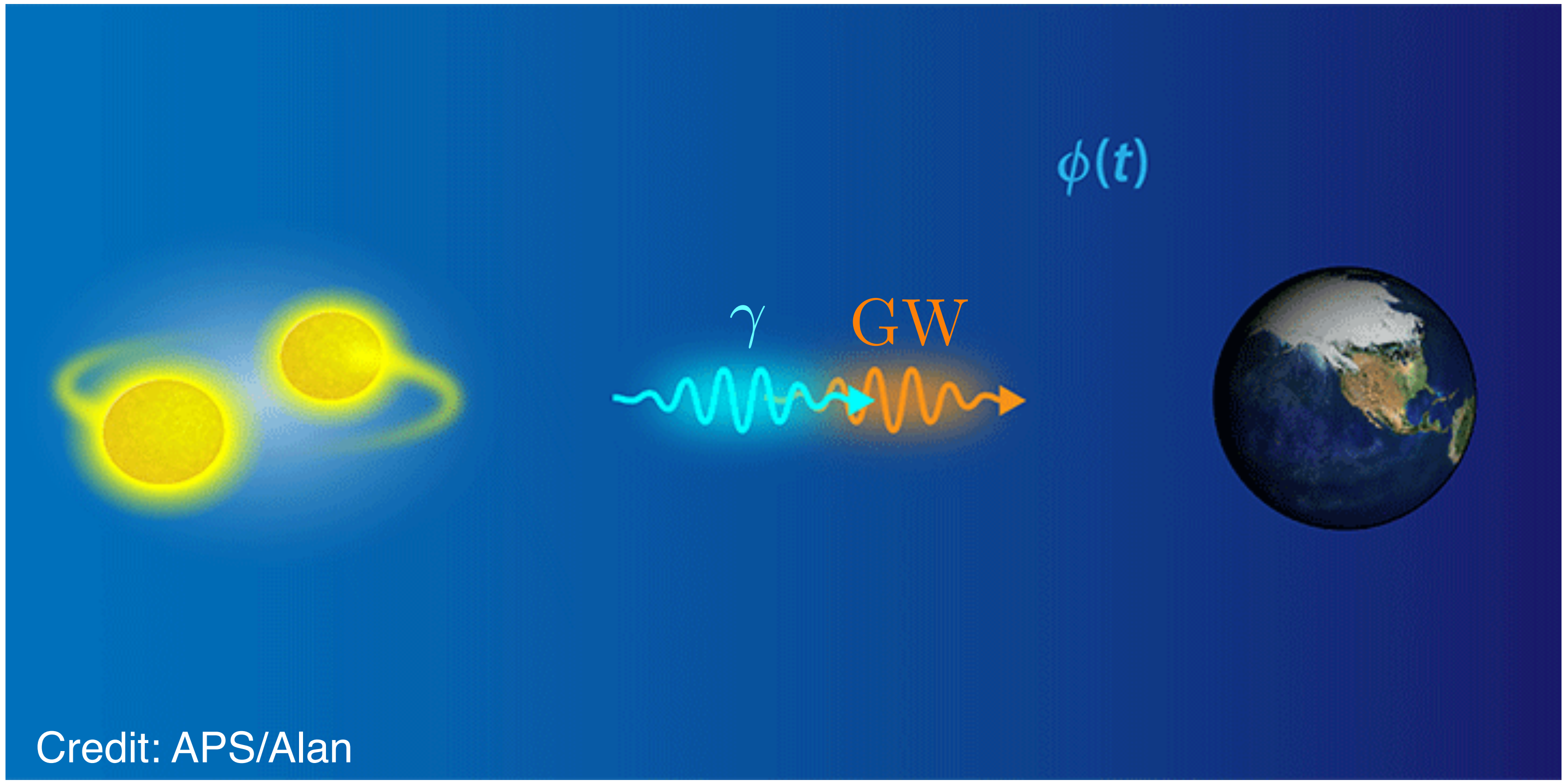
Speed of gravity



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

Modified gravitational wave propagation

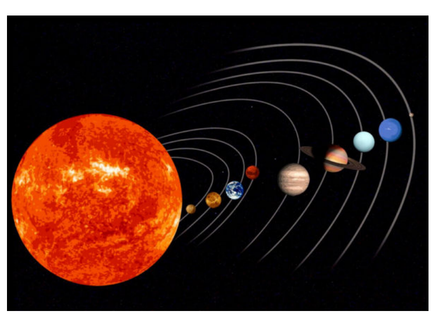
Modified gravity spontaneously breaks Lorentz Invariance. Acts like a medium, where gravitons are absorbed and dispersed. Effects accumulate on long time-scale.

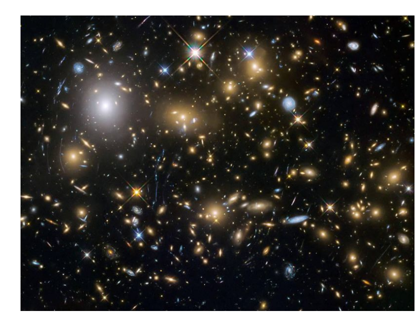


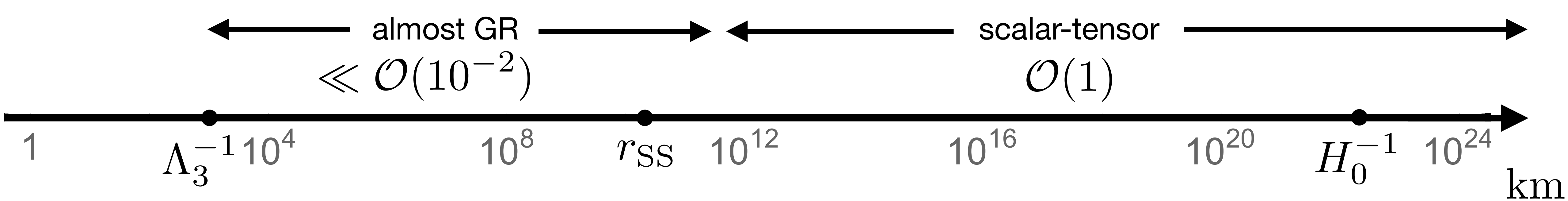
Generalized scalar-tensor theories

$$
\begin{aligned}
\mathcal{L} = {} & G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \qquad\qquad \Box\phi \equiv \phi_{;\mu}^{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu} \\
& - 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right] \\
& + G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right] \\
& - F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'} \\
& - F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}
\end{aligned}
$$

Self-acceleration and screening: large classical scalar field nonlinearities







Generalized scalar-tensor theories

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

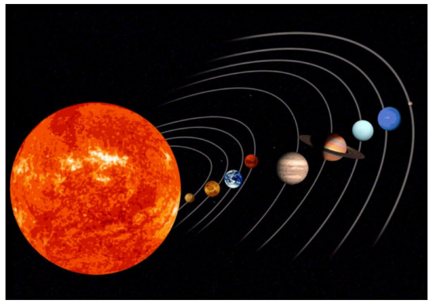
~~$$-2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right]$$~~

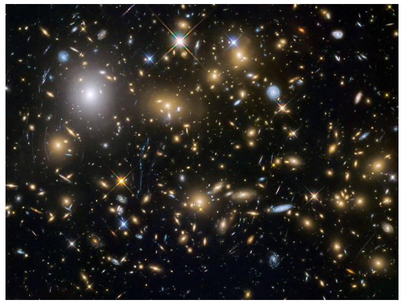
~~$$+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right]$$~~

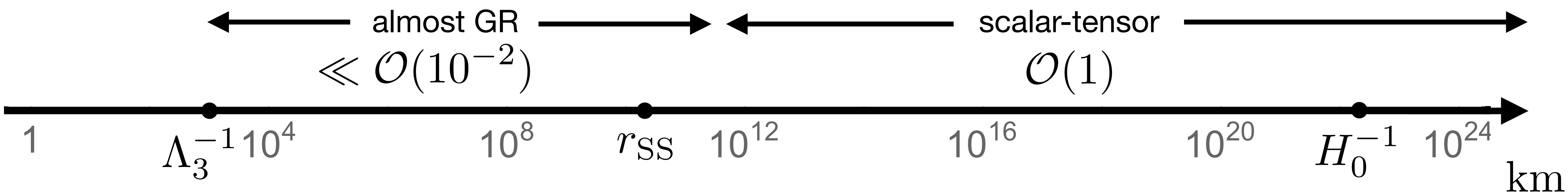
~~$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$~~

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

Self-acceleration and screening: large classical scalar field nonlinearities

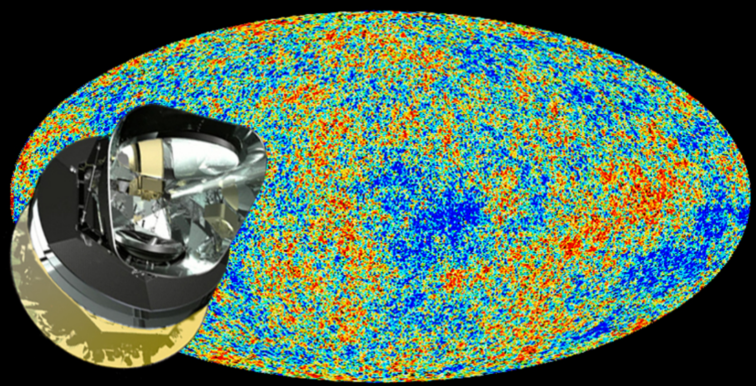






The future

CMB: WMAP 2001-10,
Planck 2010-15, …

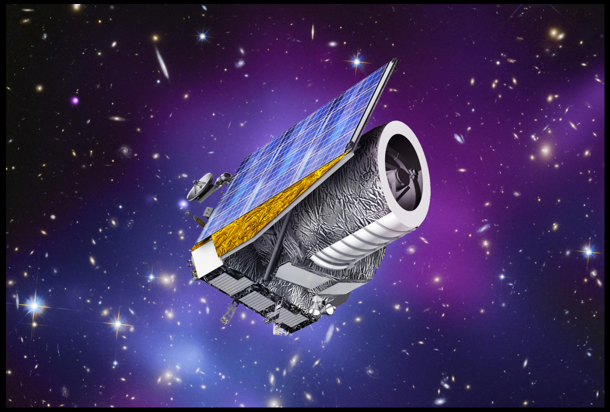


LSS: SDSS 2010-,
DES 2012-, …

GWs: LIGO/Virgo/Kagra

CMB polarisation >2030

Euclid: more to come!



LISA 2034, ET 2040s