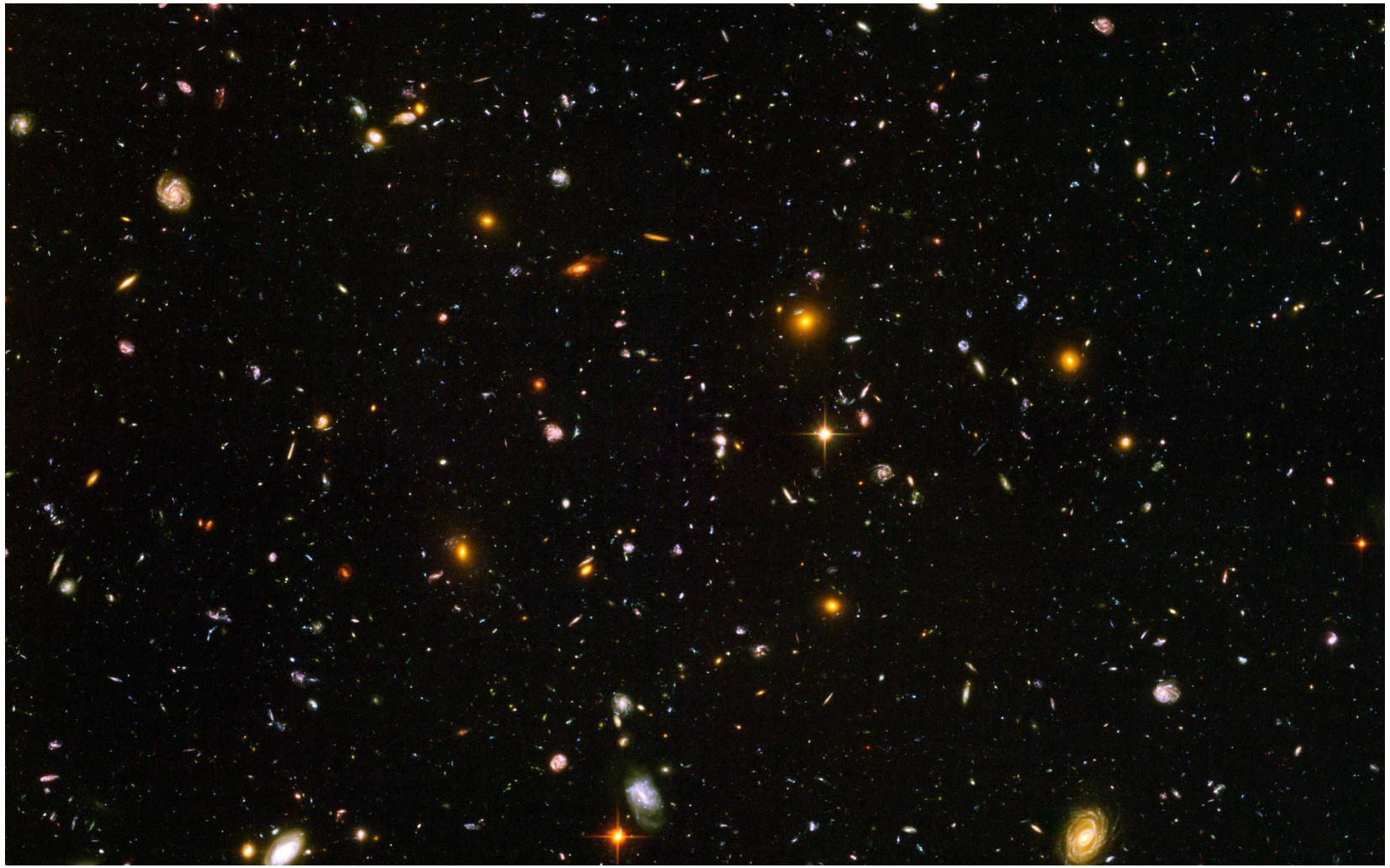
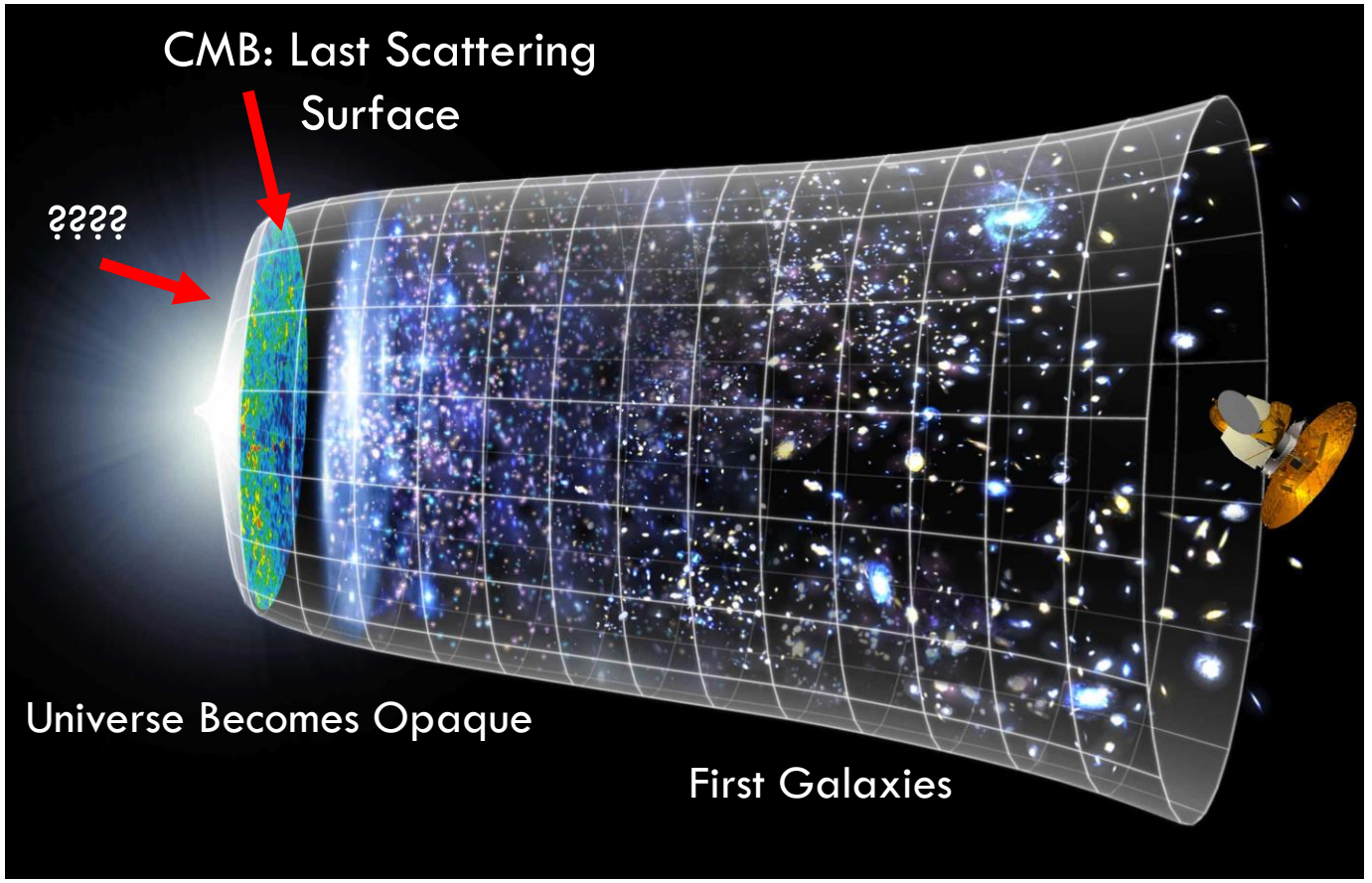
CRASH COURSE ON THE BIG BANG



SAM PASSAGLIA – POSTDOC COLLOQIUM – NOV 2021



As time goes on we see more and more of the Universe

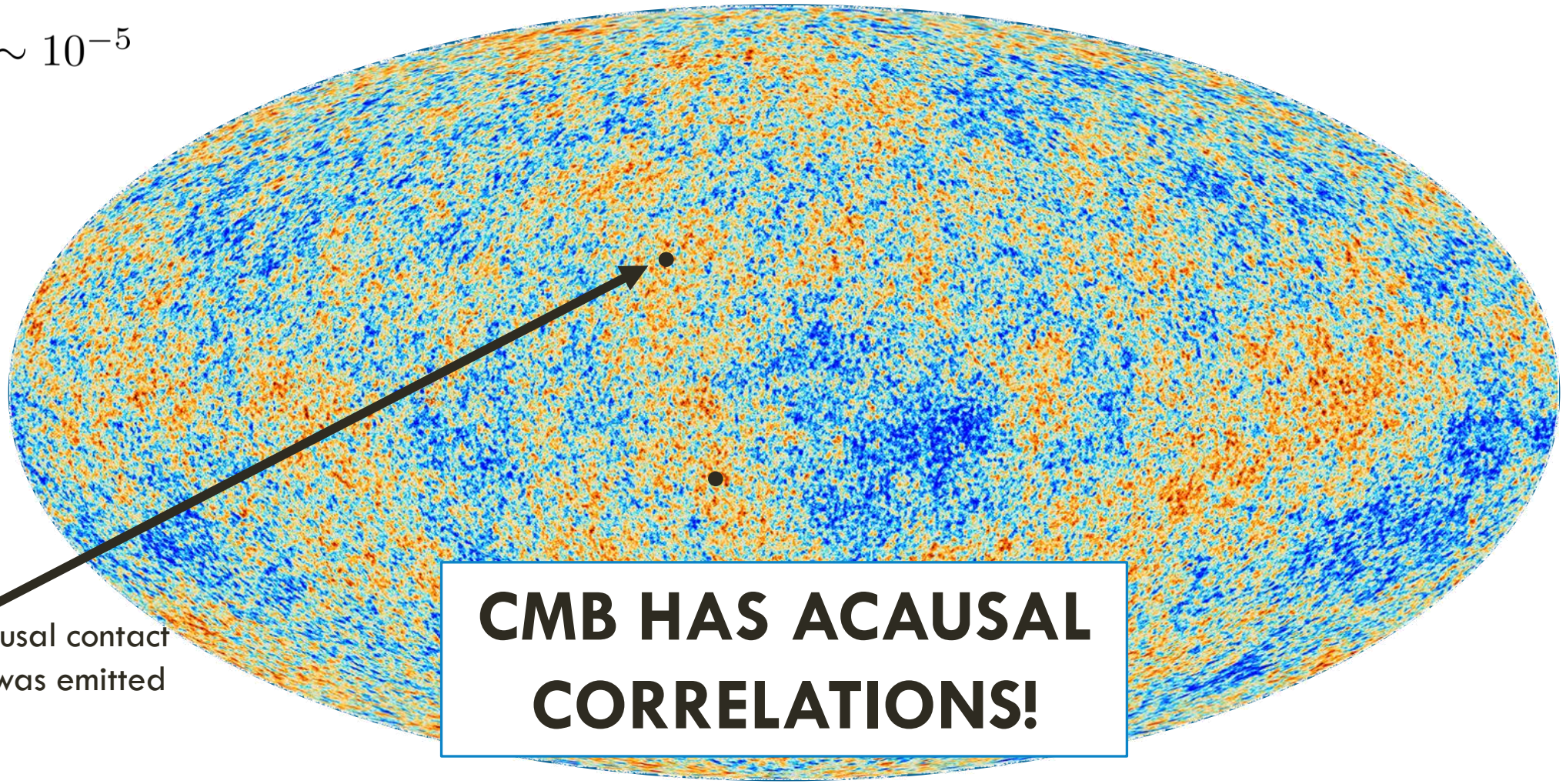
Comoving Horizon Grows for $w > -1/3$

$\sim H^{-1}/a$

THE COSMIC MICROWAVE BACKGROUND

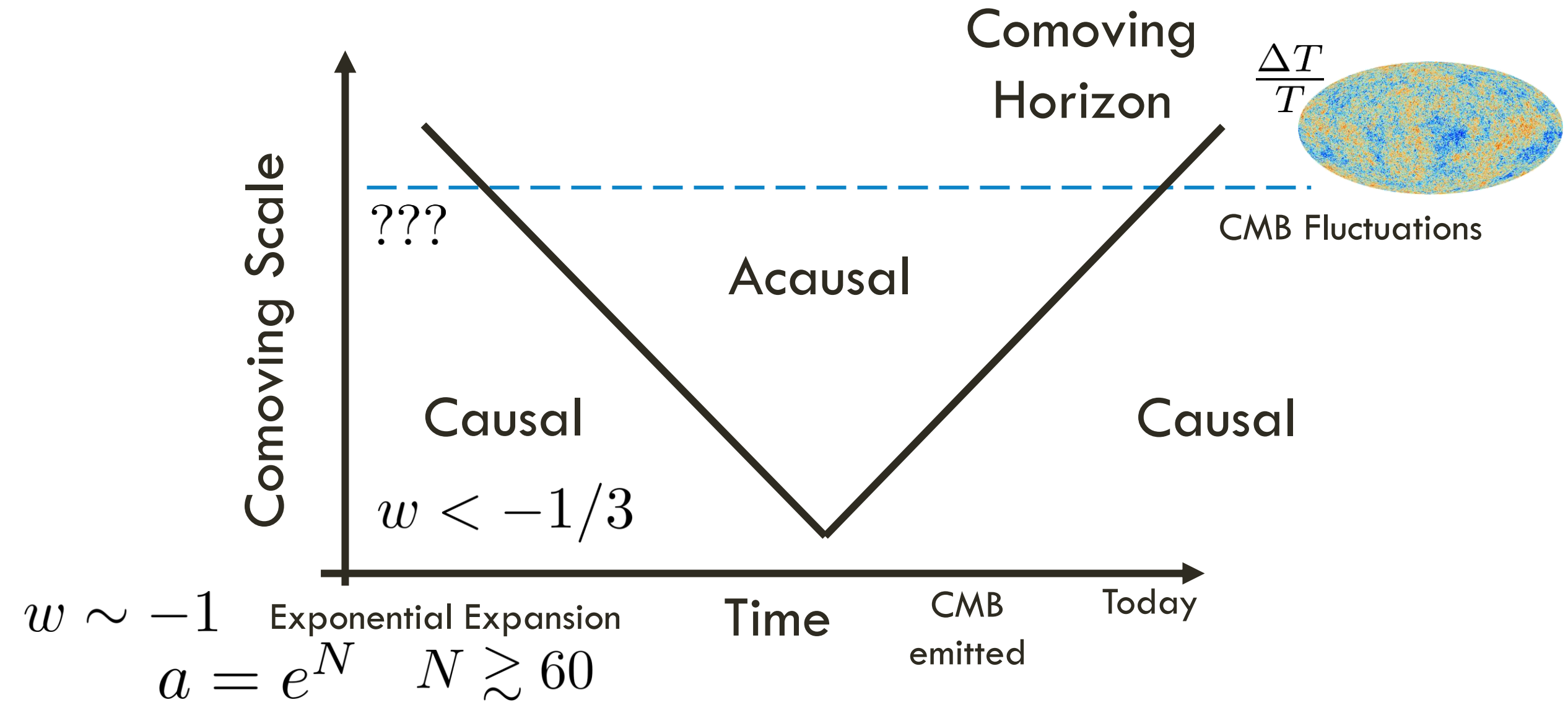
$$T_{\mathrm{CMB}} = 2.725\ \mathrm{K}$$

$$\frac{\Delta T}{T} \sim 10^{-5}$$

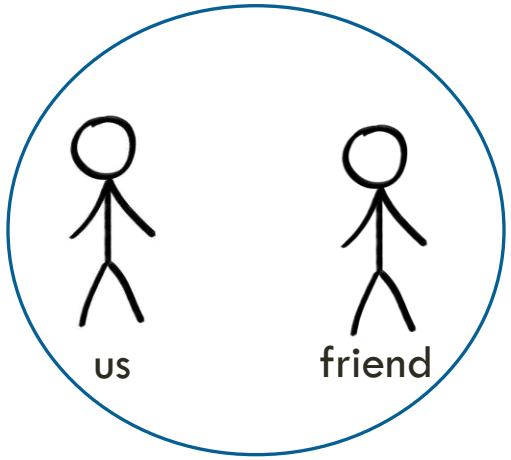


Region in causal contact when CMB was emitted

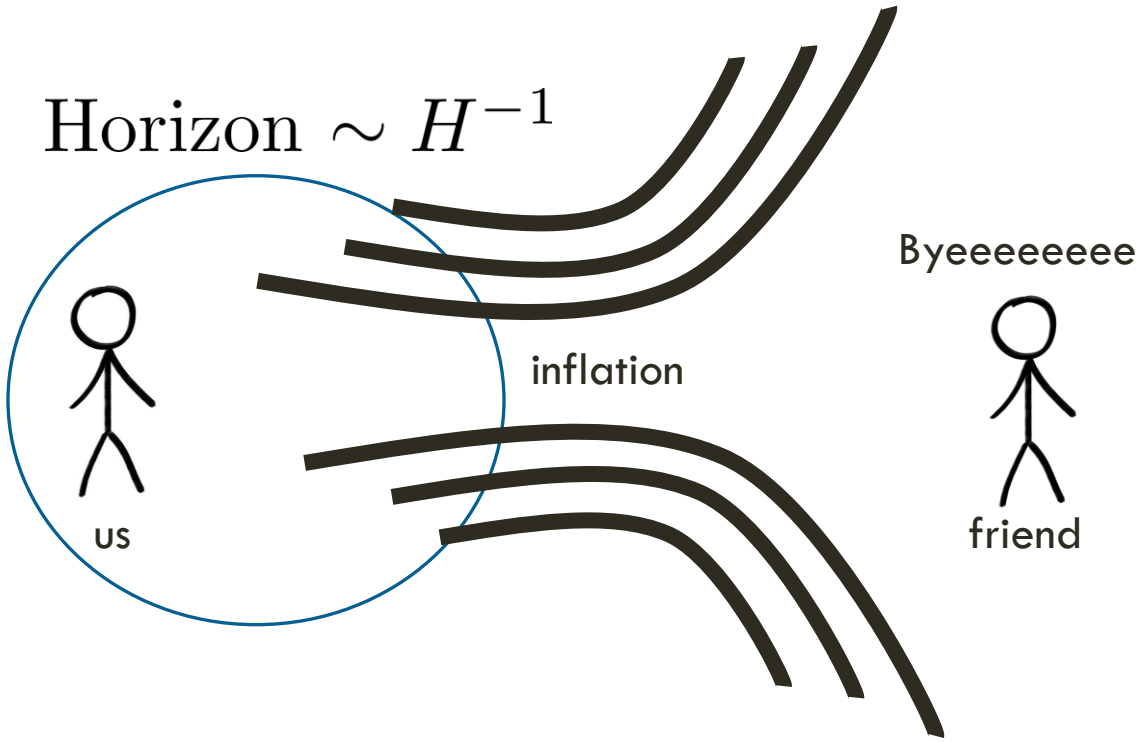
CMB HAS ACAUSAL CORRELATIONS!


Comoving Horizon
$\frac{\Delta T}{T}$
CMB Fluctuations
???
Acausal
Comoving Scale
Causal
$w < -1/3$
Causal
$w \sim -1$
Exponential Expansion
$a = e^N \quad N \gtrsim 60$
Time
CMB emitted
Today

$$\text{Horizon} \sim H^{-1}$$



Let's equilibrate!


Horizon $\sim H^{-1}$
Byeeeeeeee
inflation
us
friend

US

Hi again

friend

We agree on the temperature!

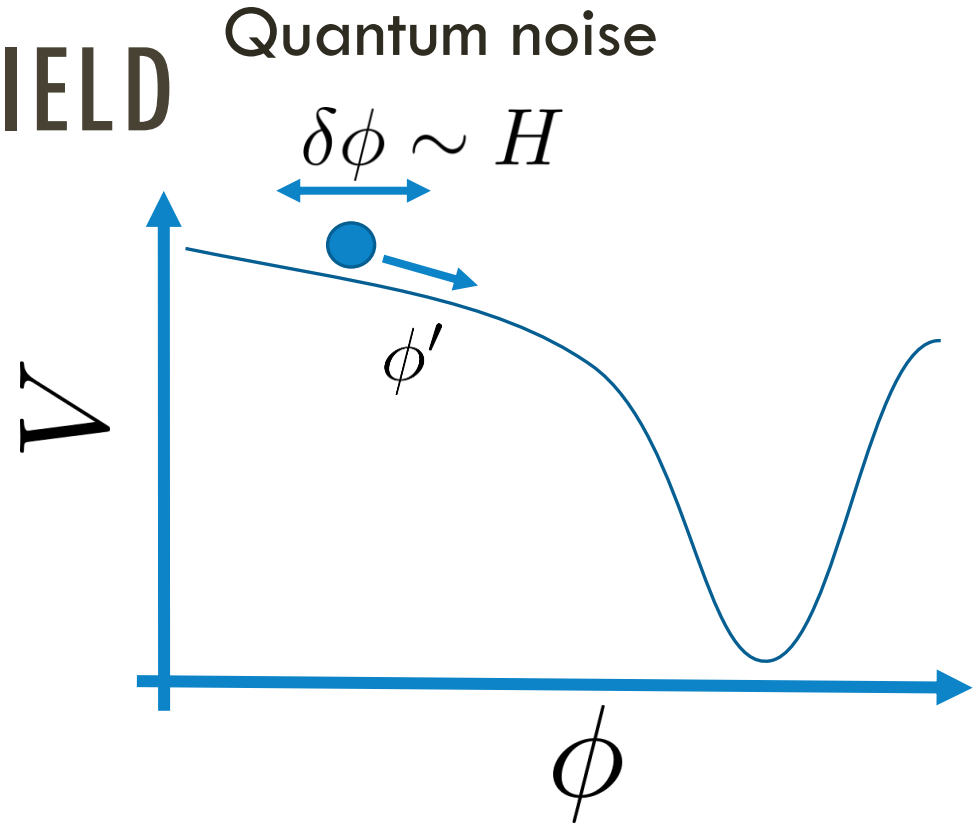
INFLATION FROM A SINGLE FIELD

Potential energy of the field ϕ dominates

$$H^2 = \frac{\rho_\phi}{3} \sim \text{constant}$$

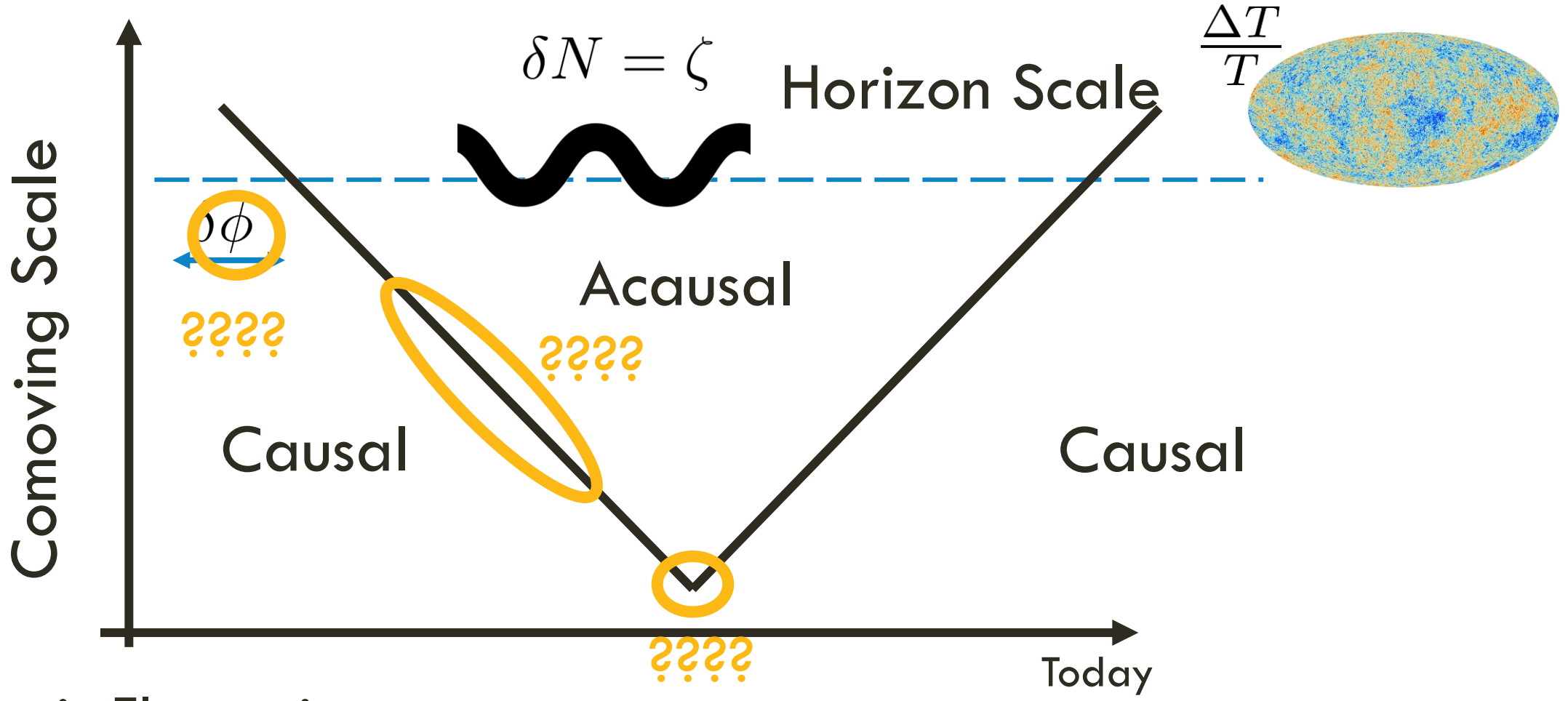
Change of Hubble controlled by velocity of the field

$$\epsilon \equiv -H'/H = \phi'^2/2$$



ϕ is a clock which counts the time to the end of inflation

Clock noise changes local duration of inflation $\delta N = \delta\phi/\phi'$



Adiabatic Fluctuations

Photons

CDM

$$\Delta^2_\zeta \sim 2 \times 10^{-9} \left(\frac{k}{k_*} \right)^{-.03}$$

STATISTICS OF ζ ENCODE PHYSICS OF ϕ

$$\langle \zeta \dots \zeta \rangle \to \langle \phi \dots \phi \rangle \to \mathcal{L}_\phi$$

$$\zeta \sim 10^{-5} \to \text{This is hard}$$

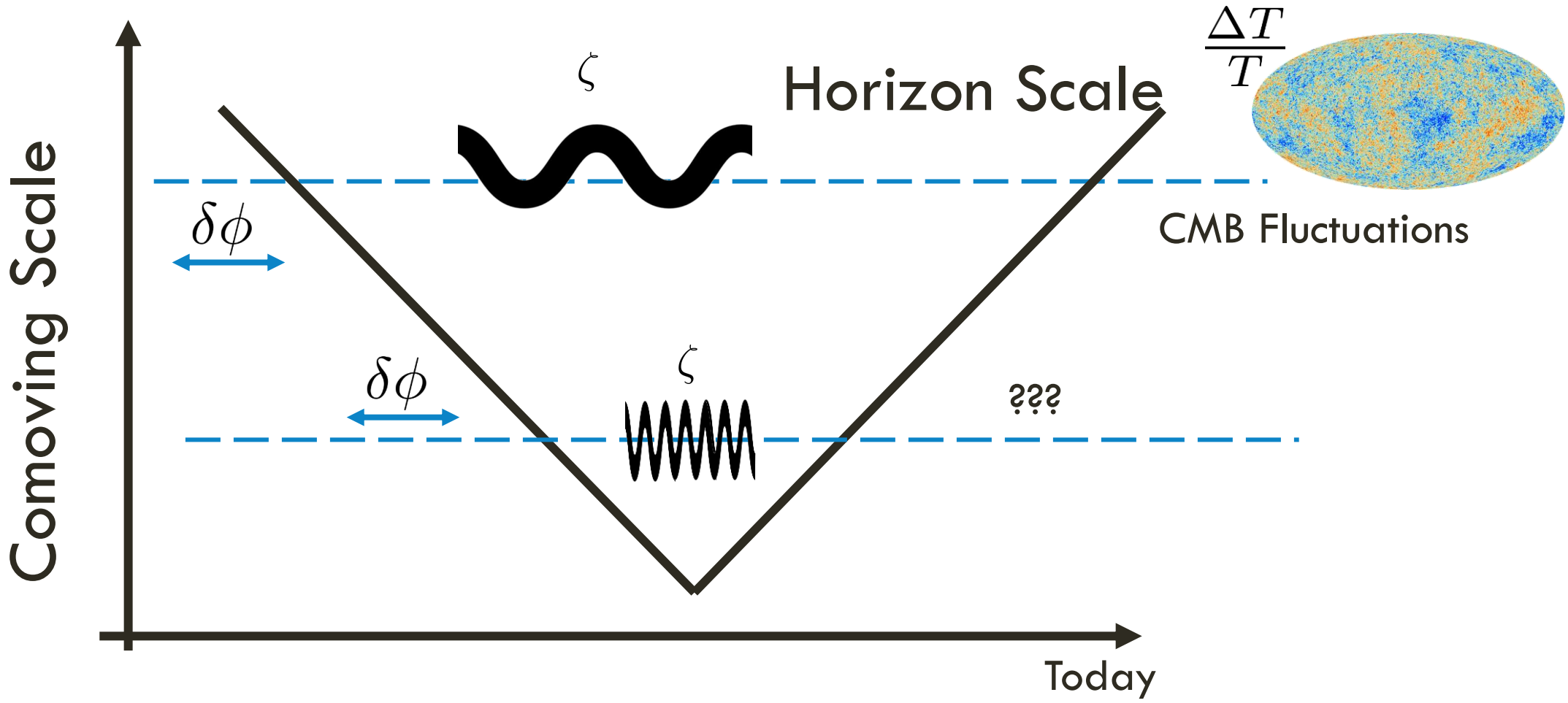
$$\lim_{k_L/k_S \to 0} \langle \zeta_L \zeta_S \zeta_S \rangle \sim f_{\rm NL}$$

- Single Clock: $f_{\rm NL} \ll 1$
- Multi Field: $f_{\rm NL} \sim \mathcal{O}(1)$?

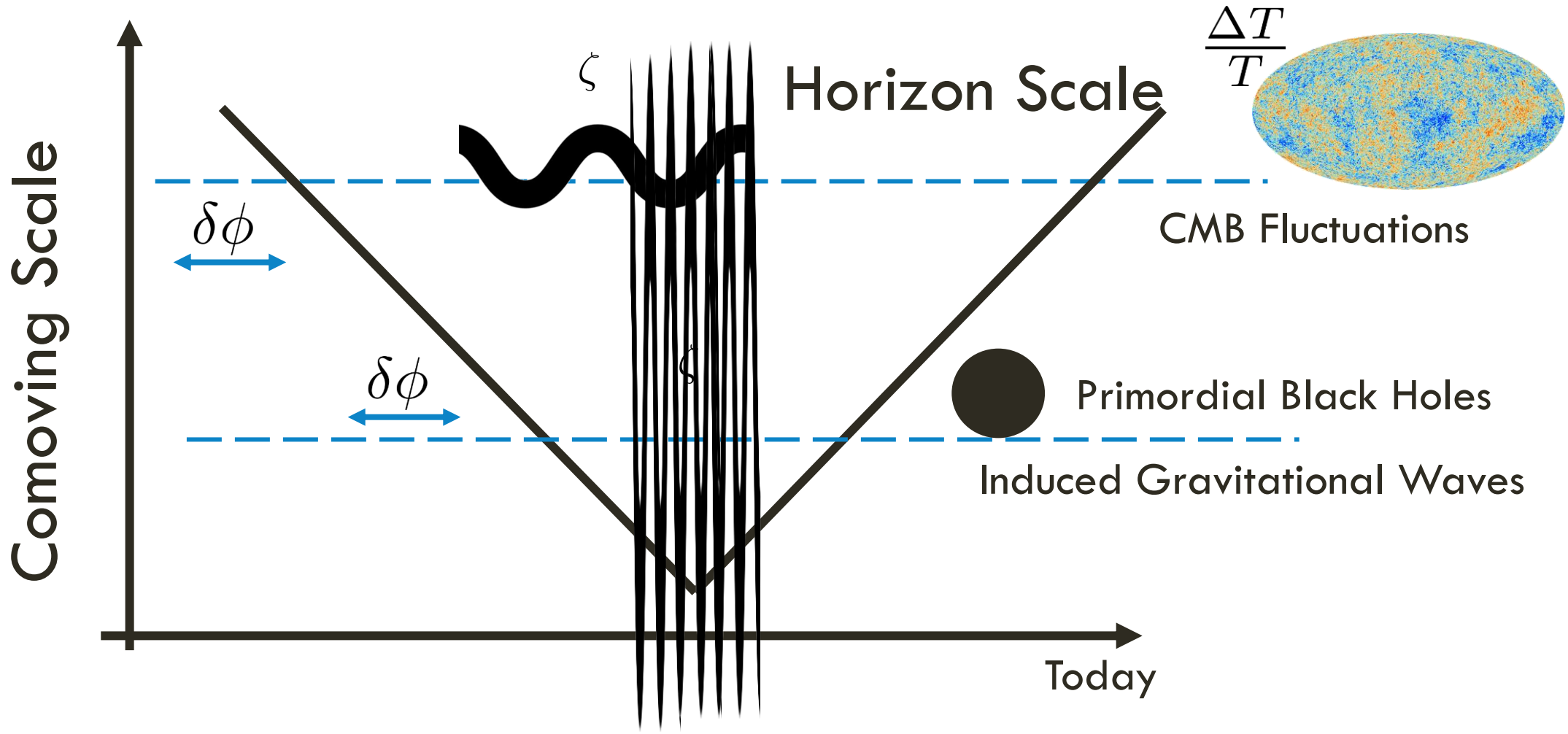
SphereX Satellite (June 2024):

$$\sigma(f_{\rm NL}) \sim 0.2$$

WHAT ABOUT THE LATE TIMES / SMALL SCALES?



WHAT ABOUT THE LATE TIMES / SMALL SCALES?



PERTURBATION TYPE ON SMALL SCALES?

Adiabatic

Photons

CDM

Fluctuations of the Inflaton $\delta\phi$

CDM Isocurvature

Photons

CDM

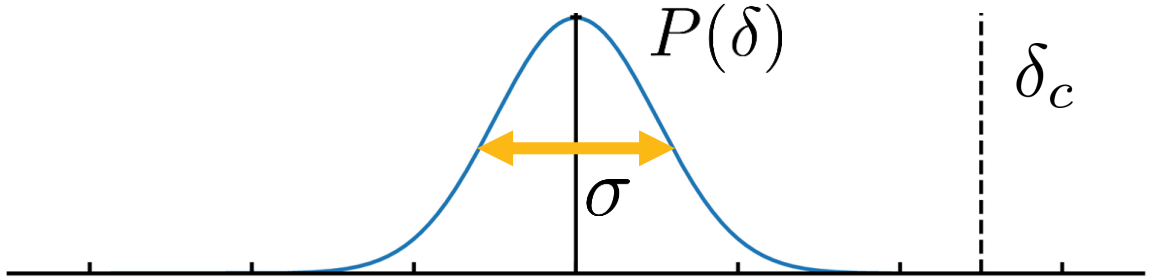
Fluctuations of any other fields

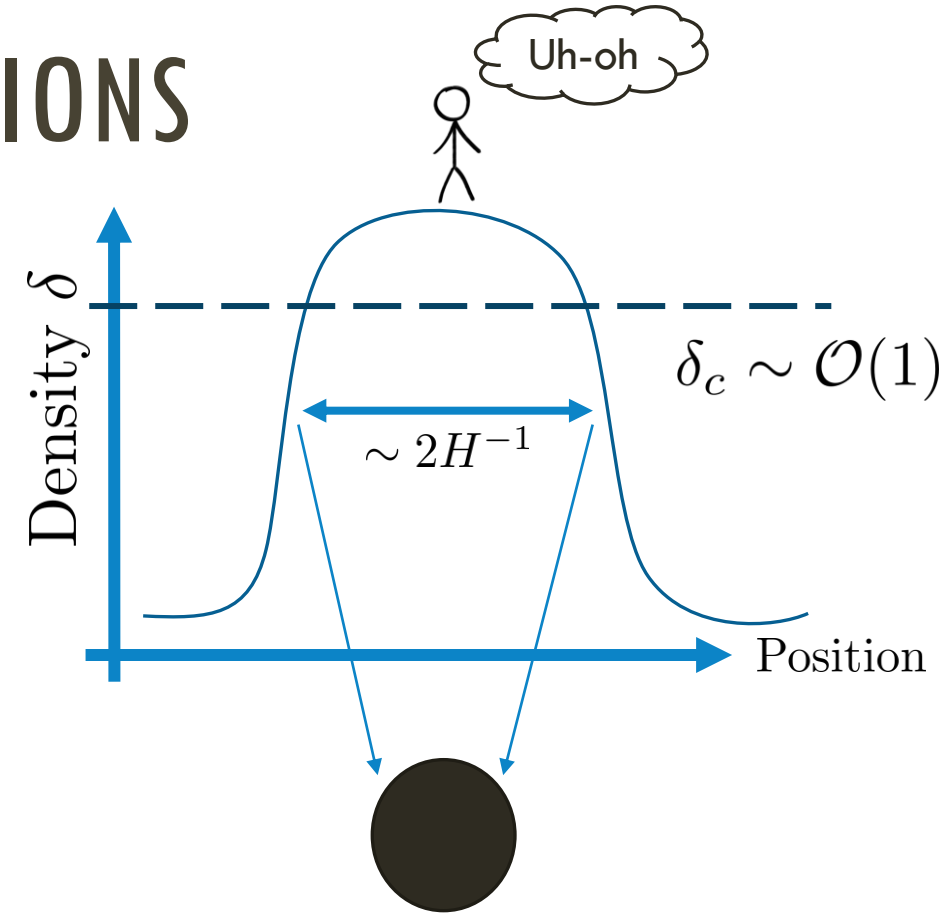
CMB Measures $\Delta_S^2 \lesssim 10^{-2} \times \Delta_\zeta^2$

What about on small scales?

PBHS FROM ADIABATIC FLUCTUATIONS

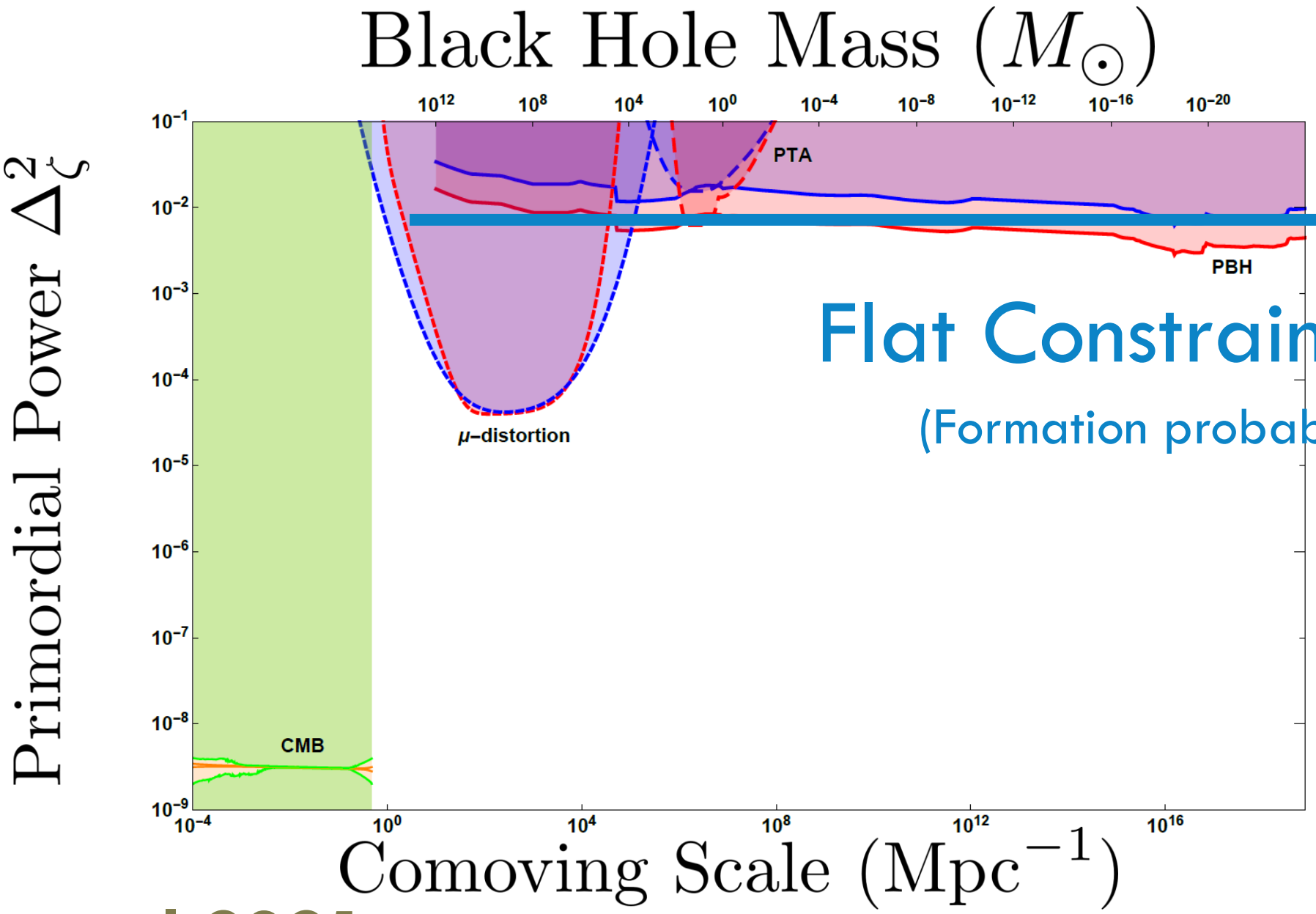
- Closed universes collapse





$$\beta \equiv \left.\frac{\rho_{\rm PBH}}{\rho_{\rm tot}}\right|_{\rm formation} \sim \int_{\delta_c}^{\infty} P(\delta) d\delta \sim \mathrm{erfc}\left(\frac{\delta_c}{\sigma\sqrt{2}}\right)$$

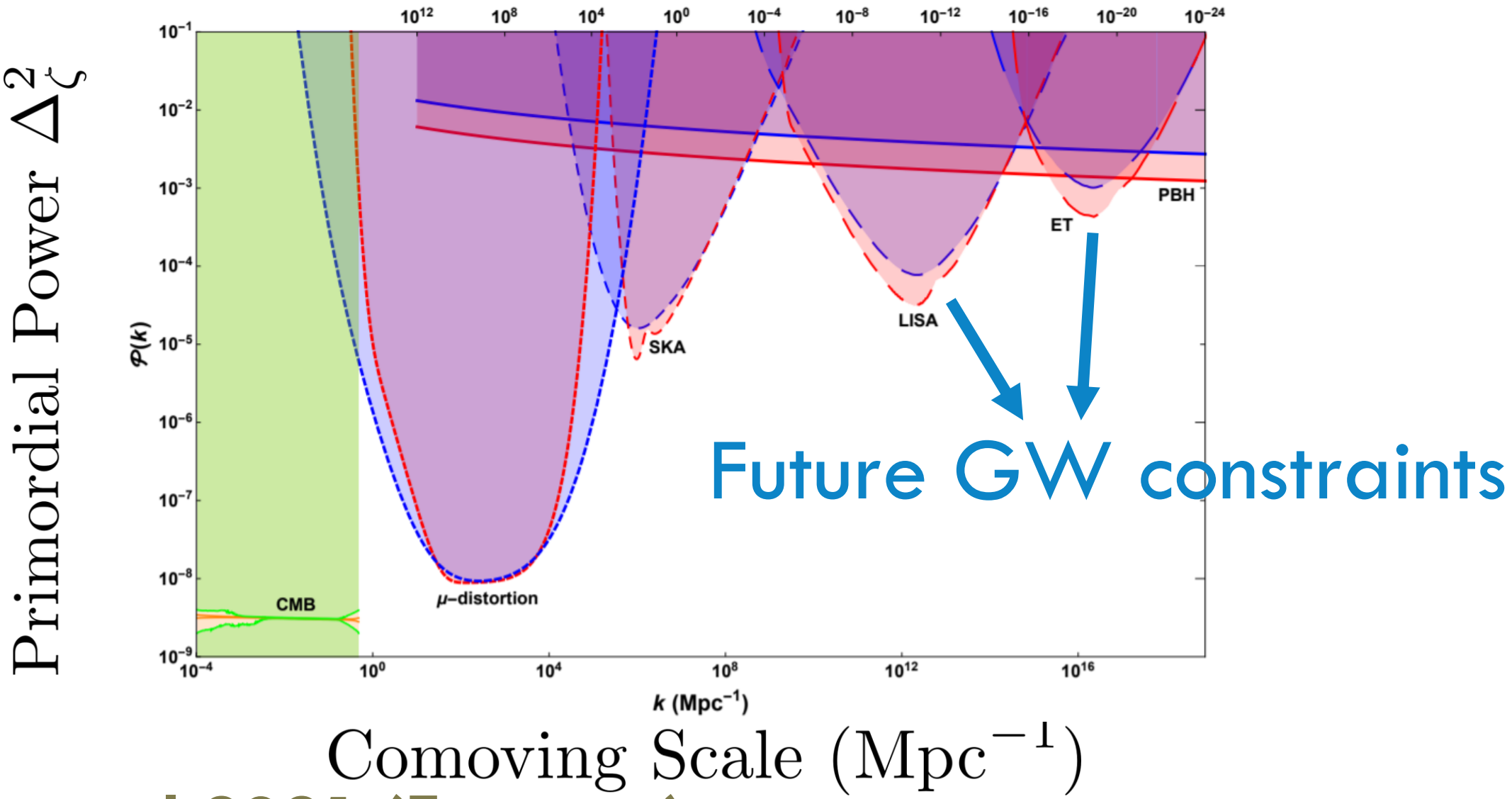
$$M_{\rm PBH} \sim \frac{4}{3}\pi R^3 \rho \sim \frac{1}{2GH}$$



Flat Constraint $\sim 10^{-2}$

(Formation probability is steep)

Gow et al 2021



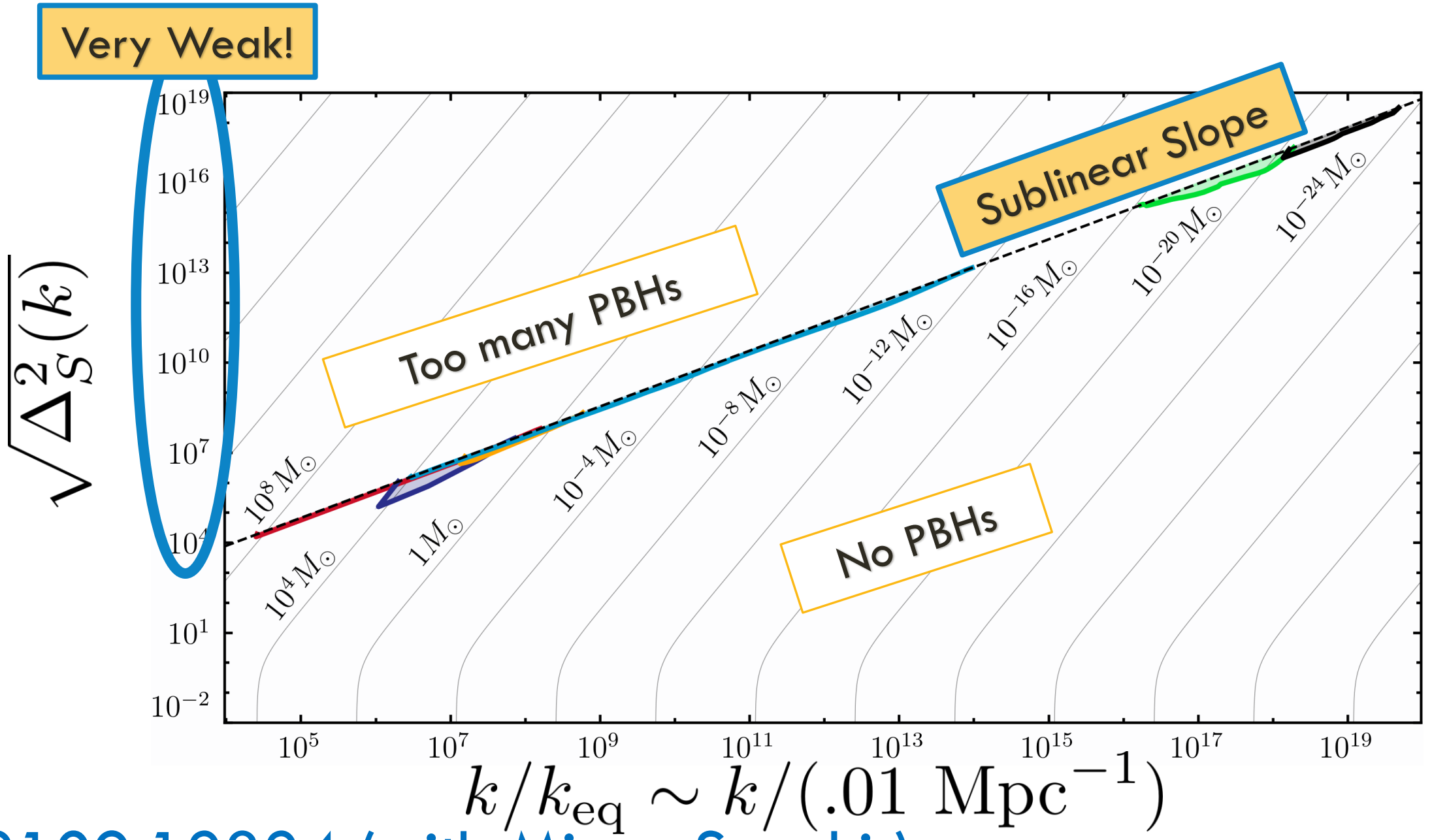
Gow et al 2021 (Forecast)

WHAT ABOUT THE ISOCURVATURE COMPONENT?

- **Large** CDM perturbation δ_c but no radiation perturbation δ_r
- For PBHs to form **metric perturbation** is large $\Psi \sim 1$
- Poisson Equation: $\Psi \sim \left(\frac{aH}{k}\right)^2 \delta \rightarrow \delta(aH = k) \sim 1$

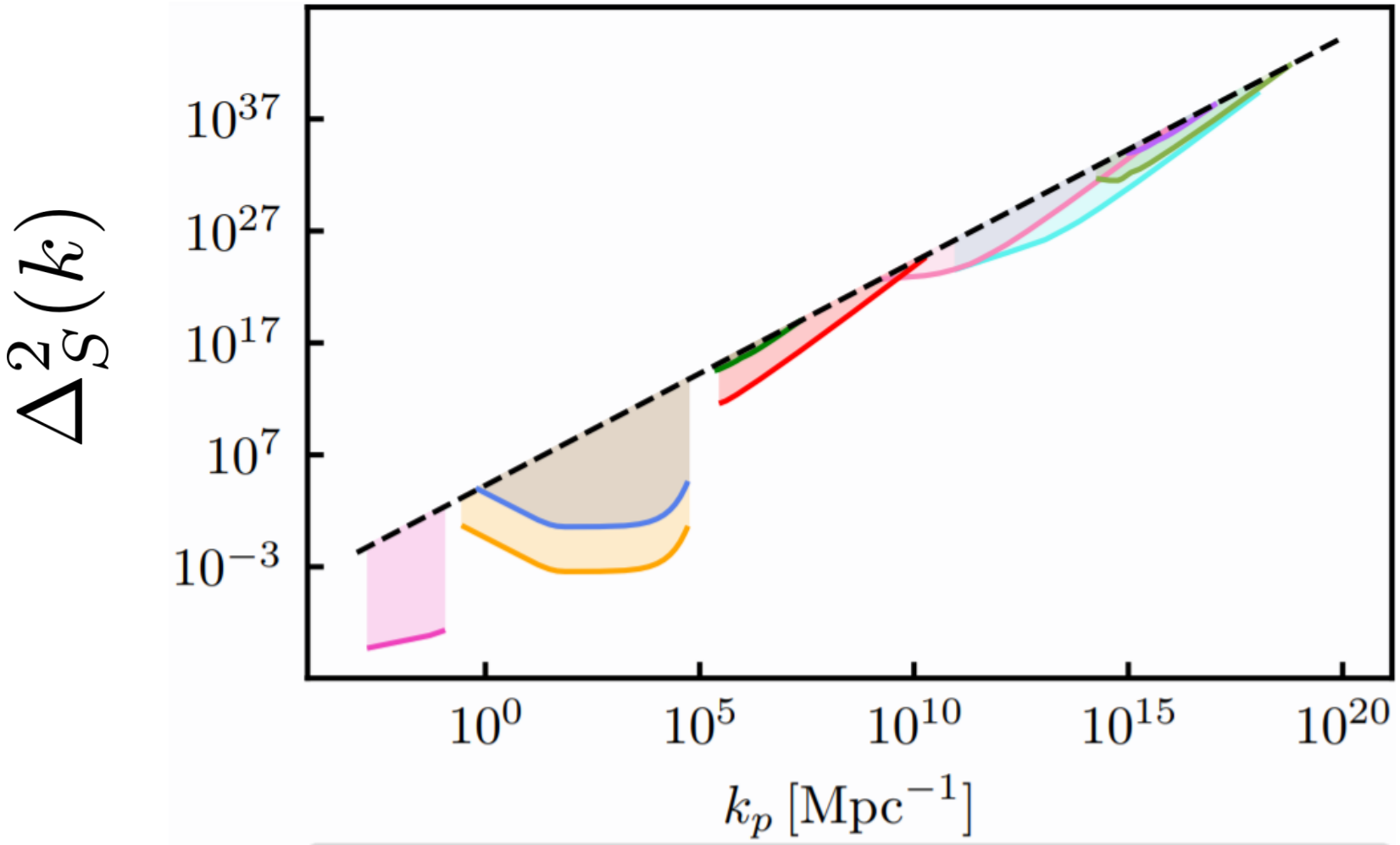
$$\delta = \frac{\rho_c}{\rho_{tot}} \delta_c \rightarrow \delta_c \sim \frac{k}{k_{\rm eq}}$$

Huge Isocurvature Fluctuations can form PBHs

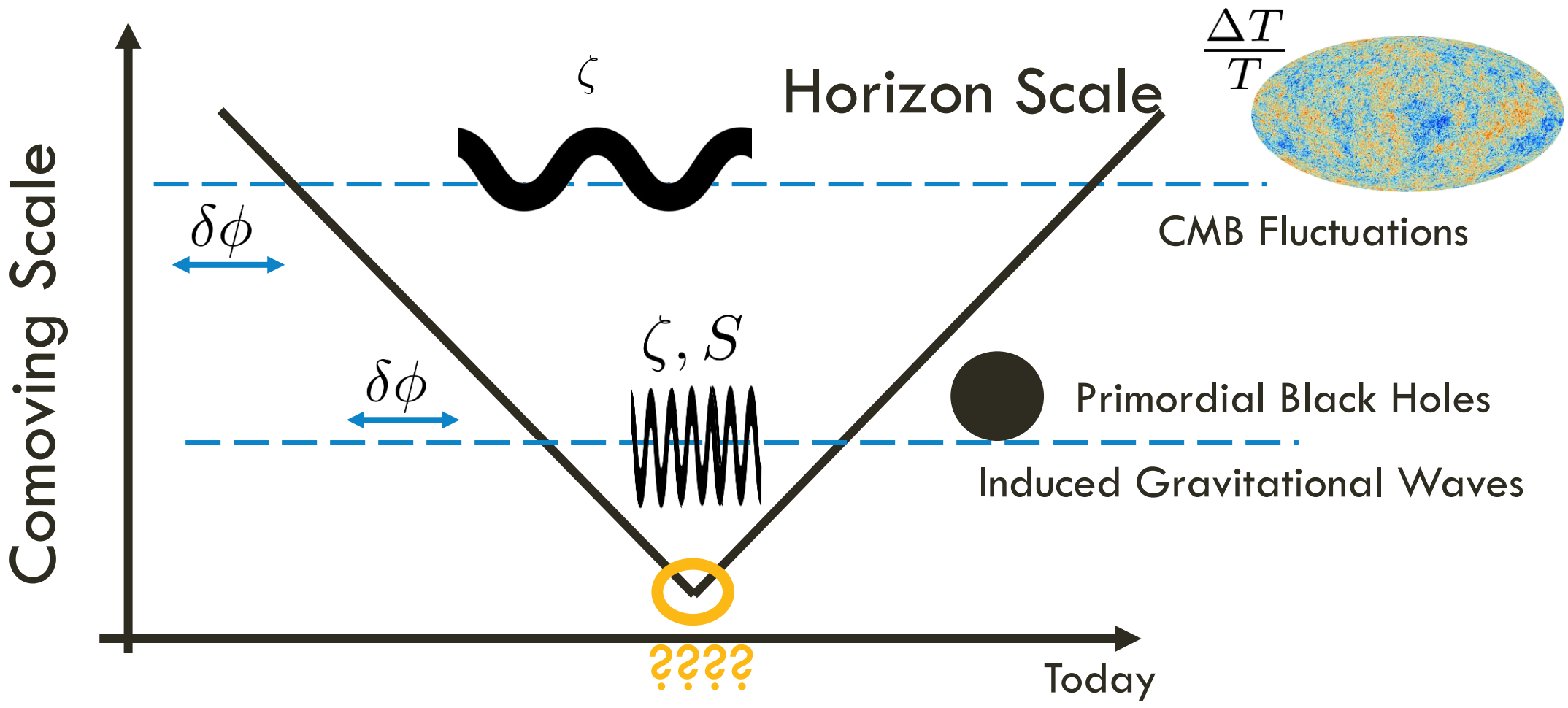


2109.12824 (with Misao Sasaki)

VERY PRELIMINARY RESULTS FOR GW CONSTRAINTS



Preliminary (with G. Domenech, S. Renaux-Petel)


Comoving Scale
ζ
Horizon Scale
$\frac{\Delta T}{T}$
$\delta\phi$
CMB Fluctuations
ζ, S
$\delta\phi$
Primordial Black Holes
Induced Gravitational Waves
????
Today

REHEATING: WE KNOW NOTHING ABOUT IT

$$\text{Somehow } \phi \rightarrow \text{Thermal SM plasma}$$

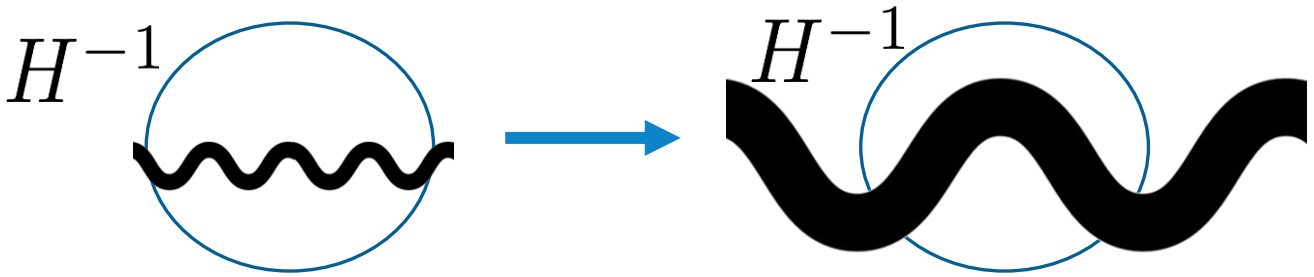
How long does this take? At what energy scale?

$$T_{\mathrm{RH}} > T_{\mathrm{BBN}} \sim \mathrm{MeV}$$

Interesting statements can be made under some assumptions

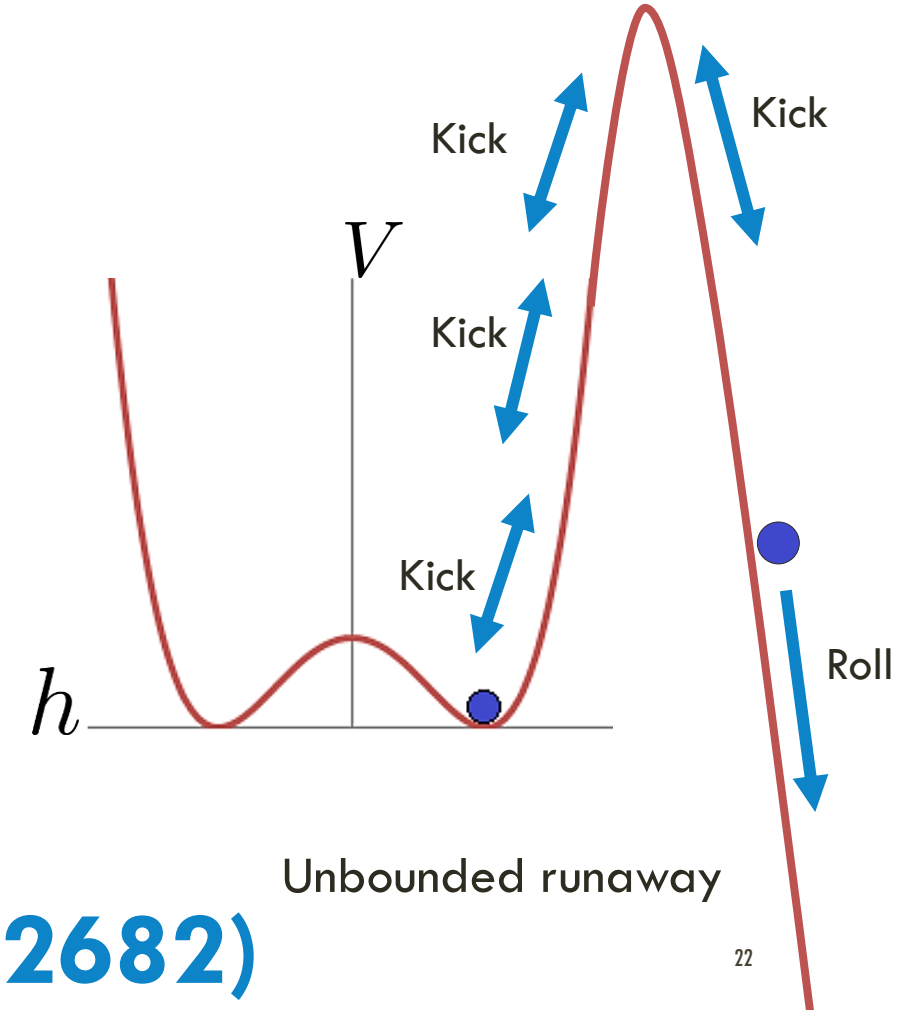
AT WHAT ENERGIES? IF SM HOLDS NOT TOO HIGH

Higgs field also gets stochastic fluctuations



If this happens even once in the observable universe it is bad

$$H_{\rm inf} \lesssim 10^{10}{\rm GeV}$$



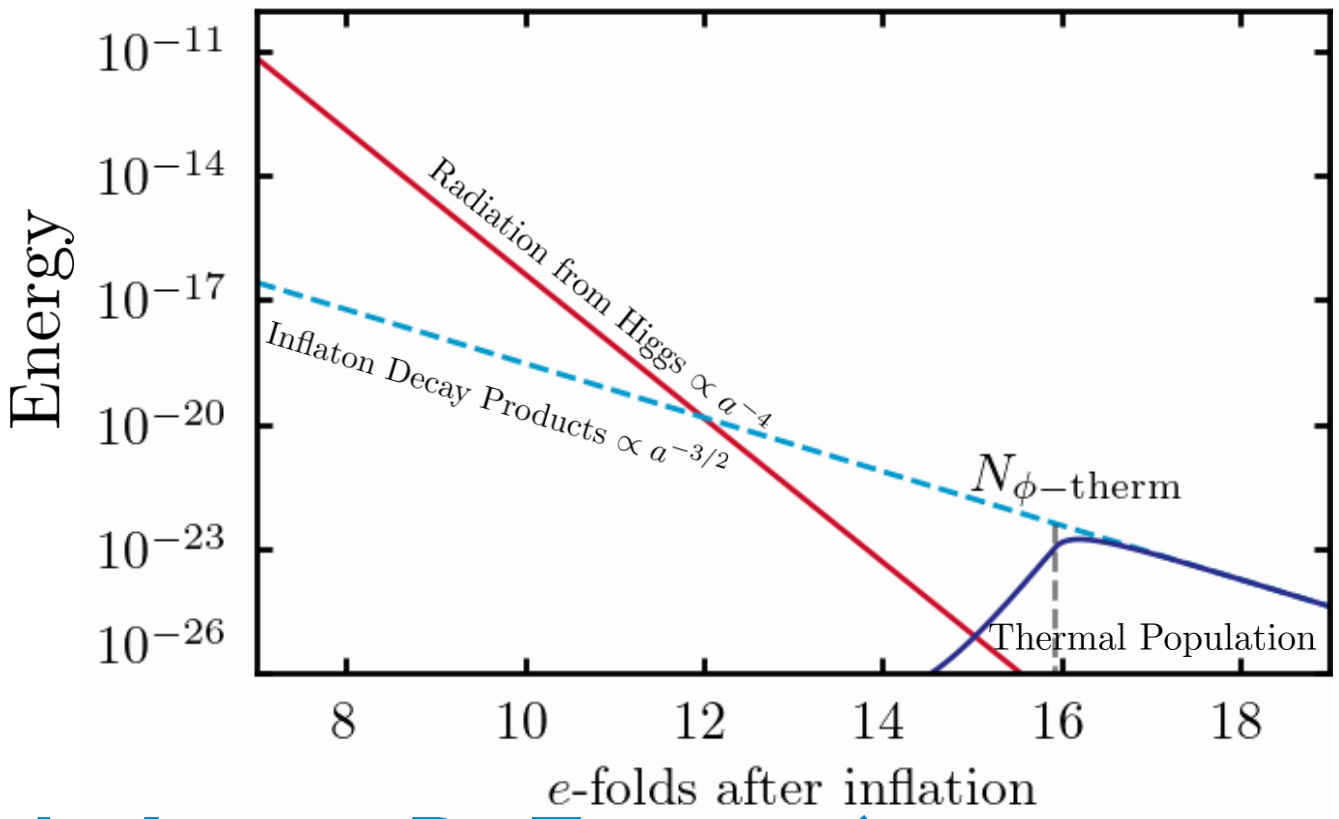
Signal of being on knife's edge: Isocurvature Fluctuations (1912.02682)

IF REHEATING IS SLOW AND SM HOLDS, HIGGS CONTROLS MAXIMUM TEMPERATURE

Higgs Condensate quickly decays to a thermal plasma

If inflation decays slowly, its contribution to the thermal plasma is delayed

$$N_{RH} \gtrsim 32 \; e\text{-folds}$$



2108.00962 (w./ W. Hu, A. Long, D. Zegeye)

Inflation is a profound, well-supported, but very sketchy model for what started the Big Bang

Data will help us fill it out:
Non-Gaussianities, Gravitational Waves, Primordial Black Holes, and Isocurvature Fluctuations