

8th Jan. 2023 @ Rencontres du Vietnam

Inflation Theory

– D'où venons-nous? Que sommes-nous? Où allons-nous? –



Yuichiro TADA Nagoya U.

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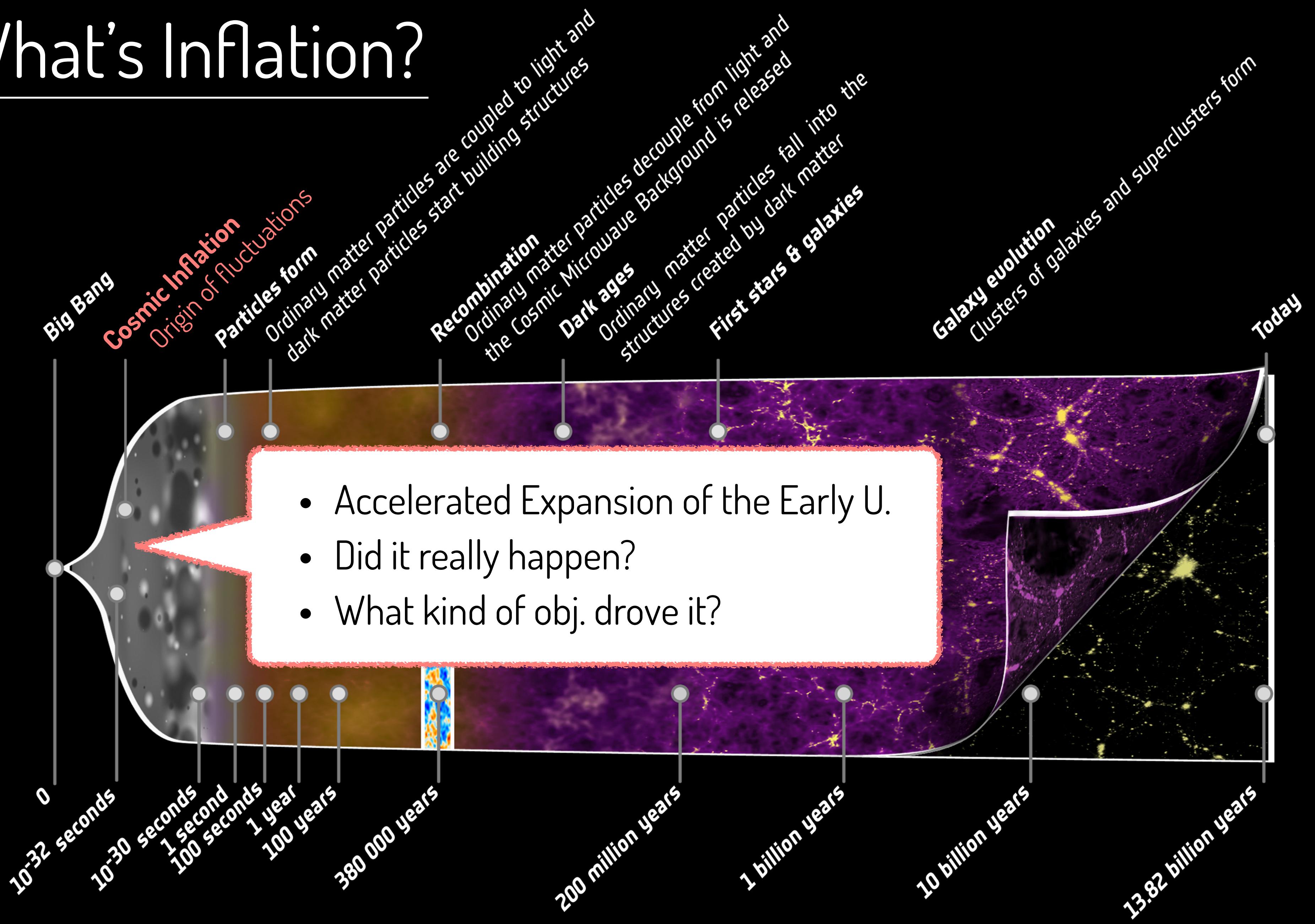
Where do we come from?

What are we?
→ Cosmologists

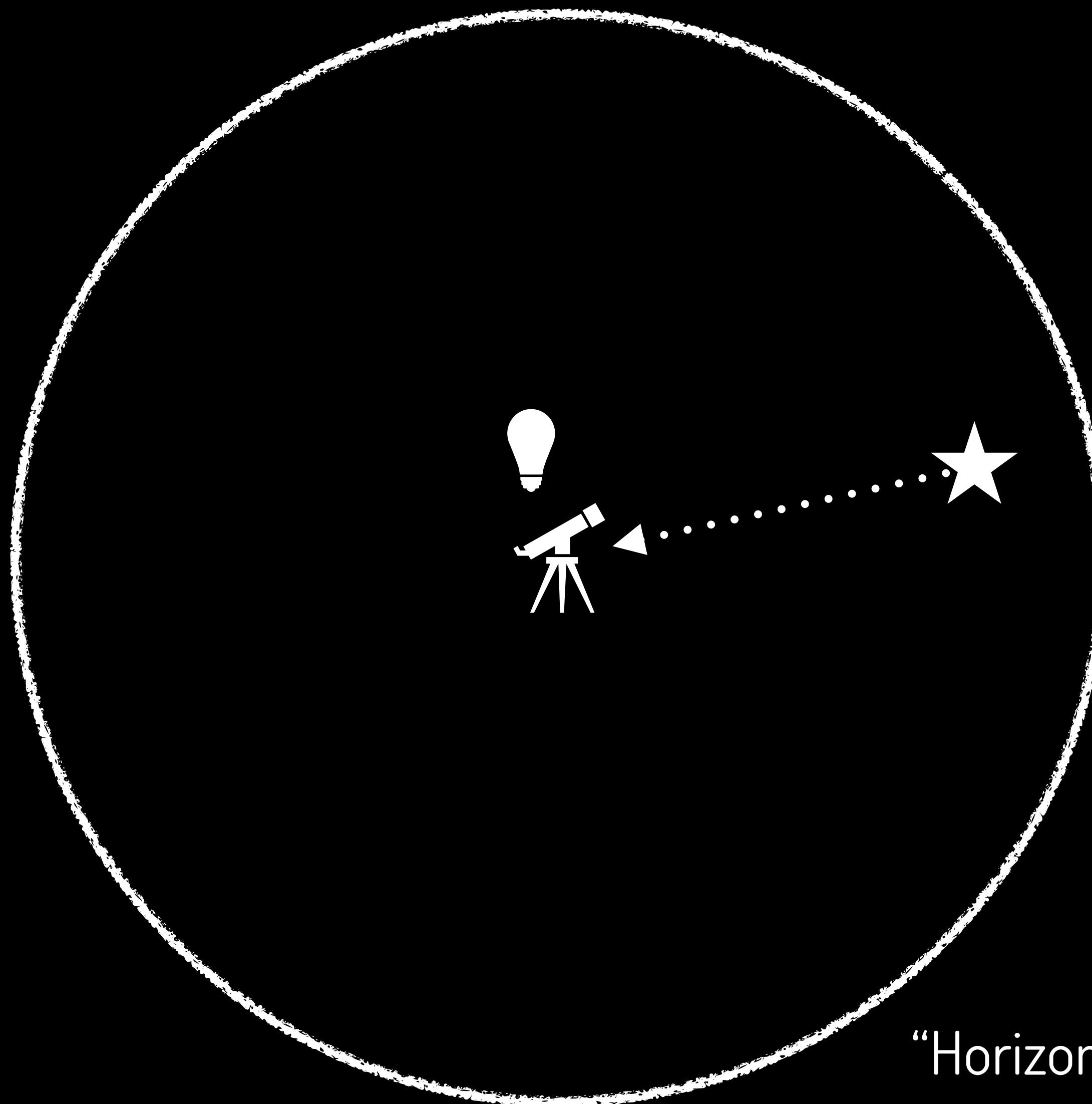
Where are we going?

Yuichiro TADA Nagoya U.

What's Inflation?

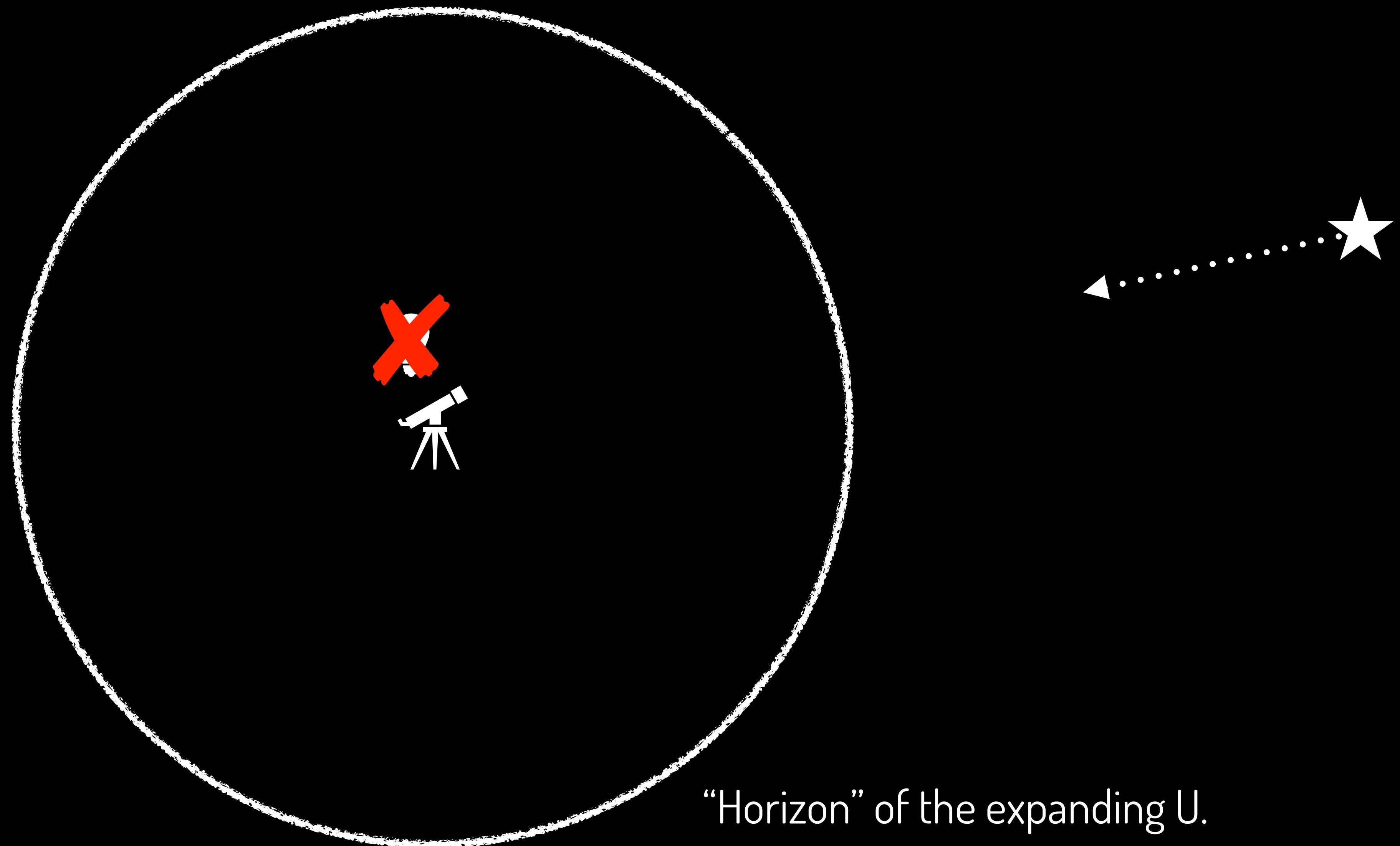


Generation of PTB

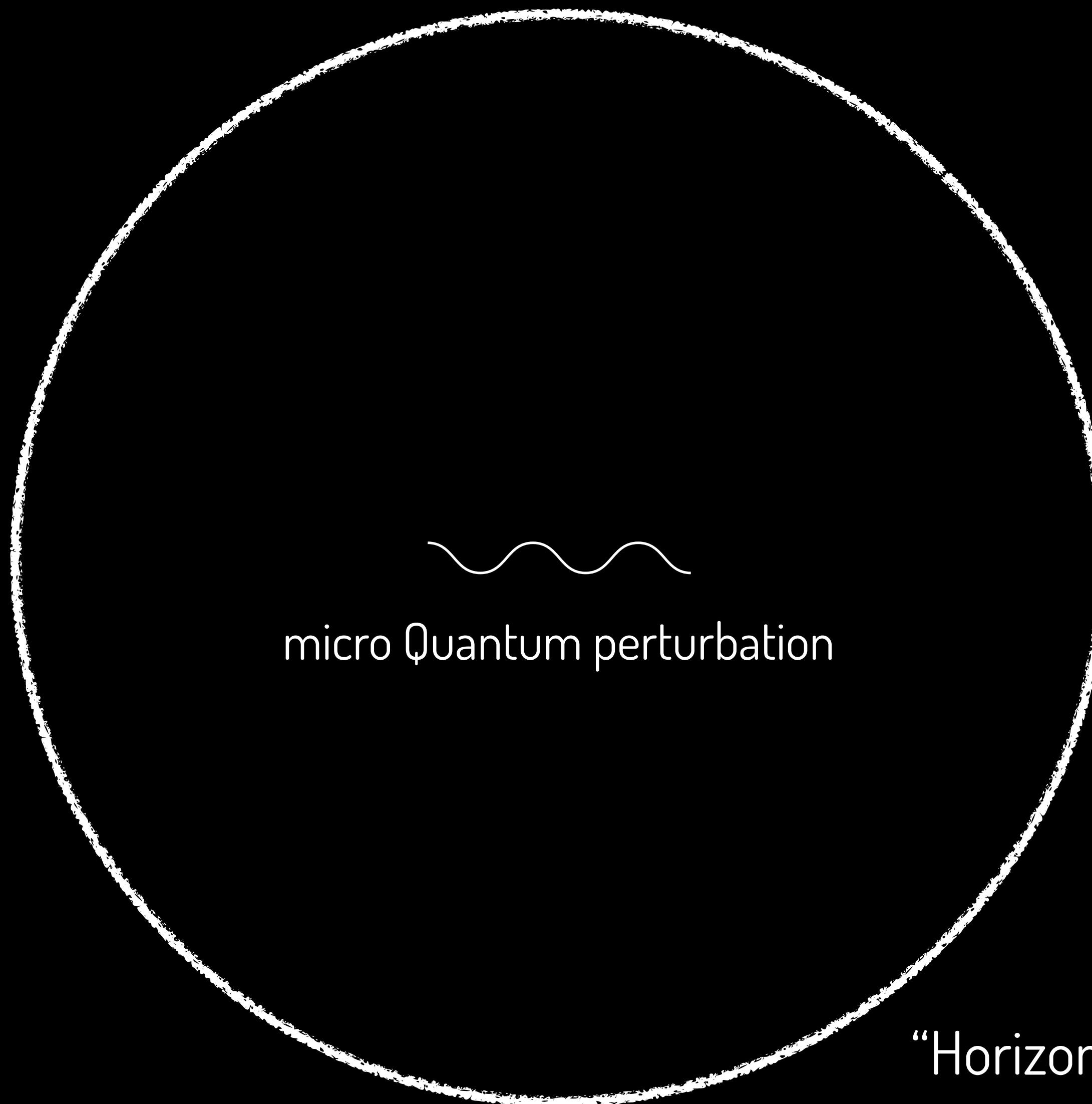


"Horizon" of the expanding U.

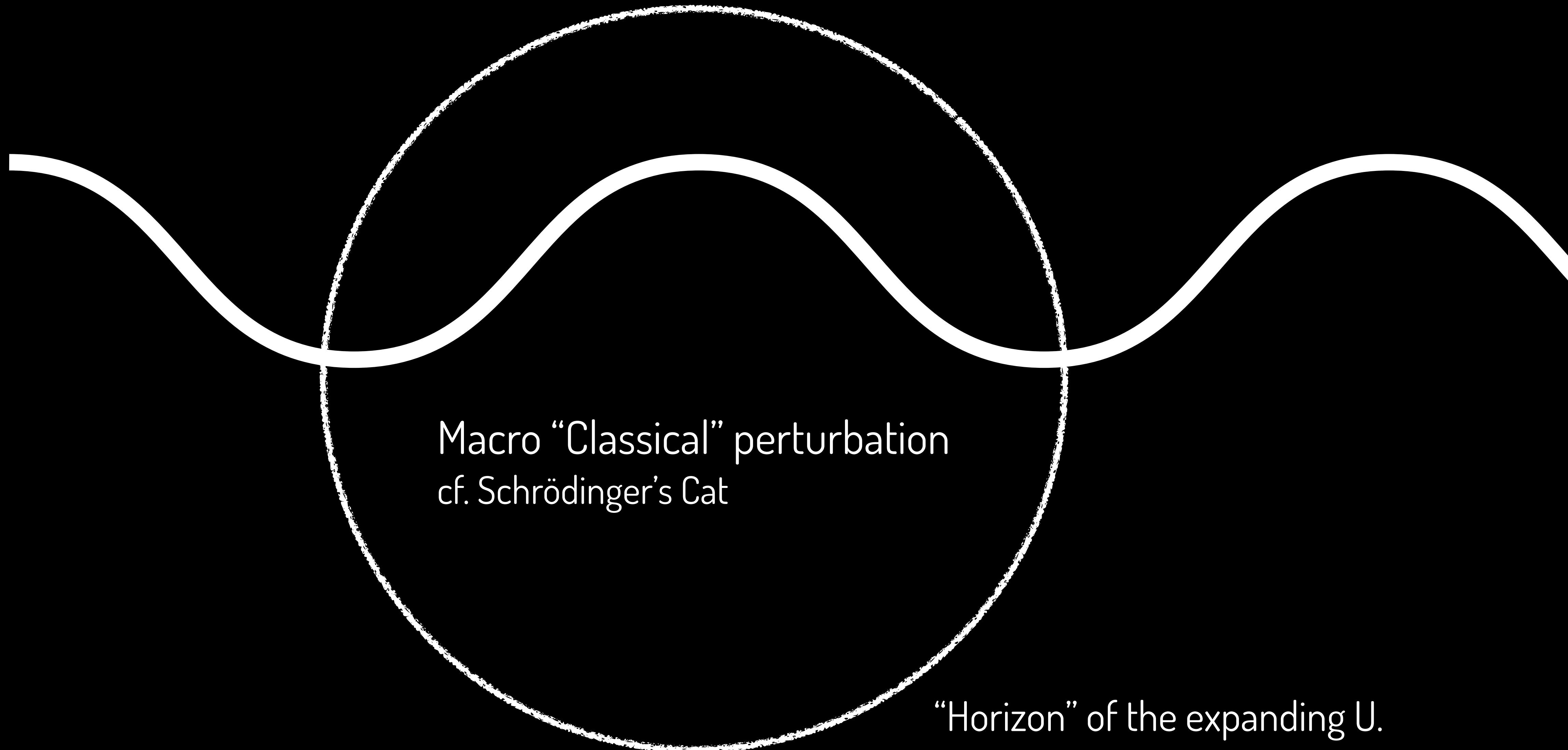
Generation of PTB



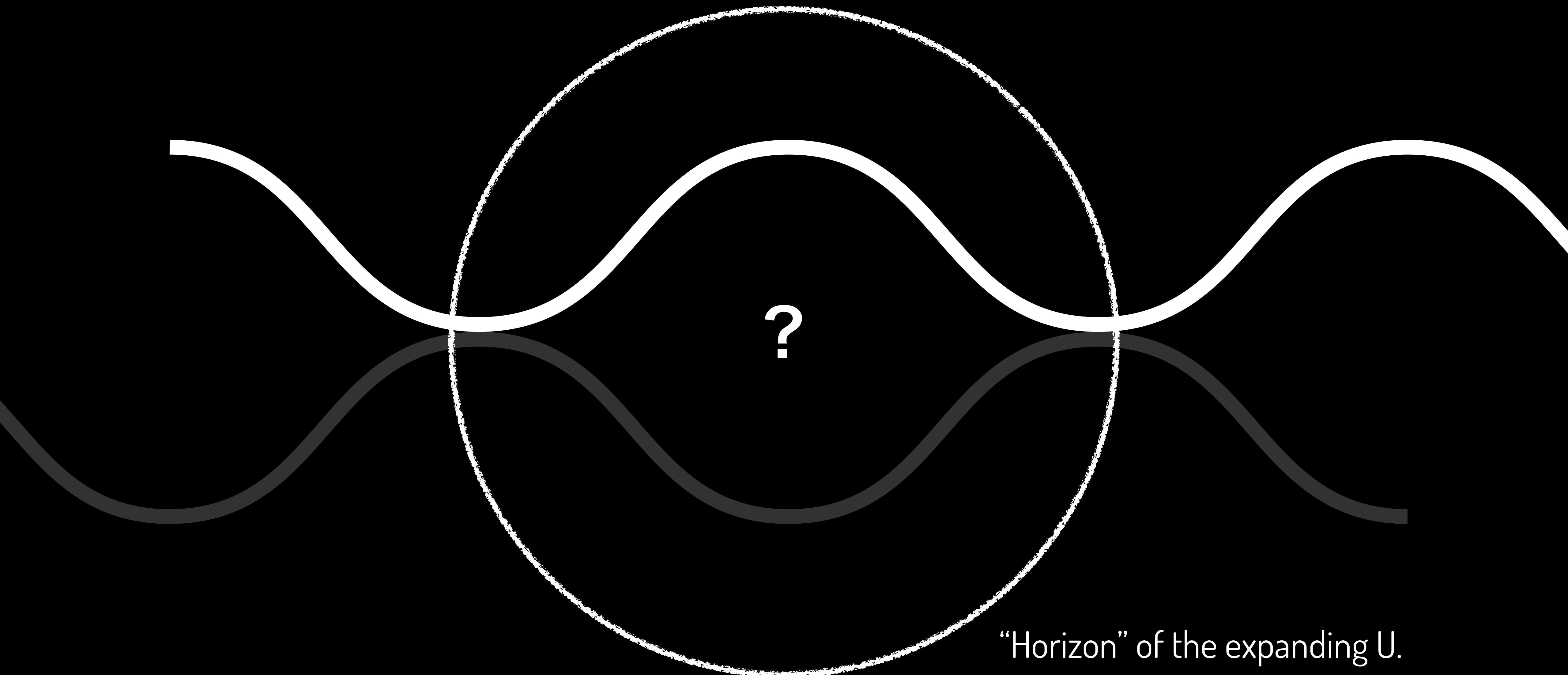
Generation of PTB



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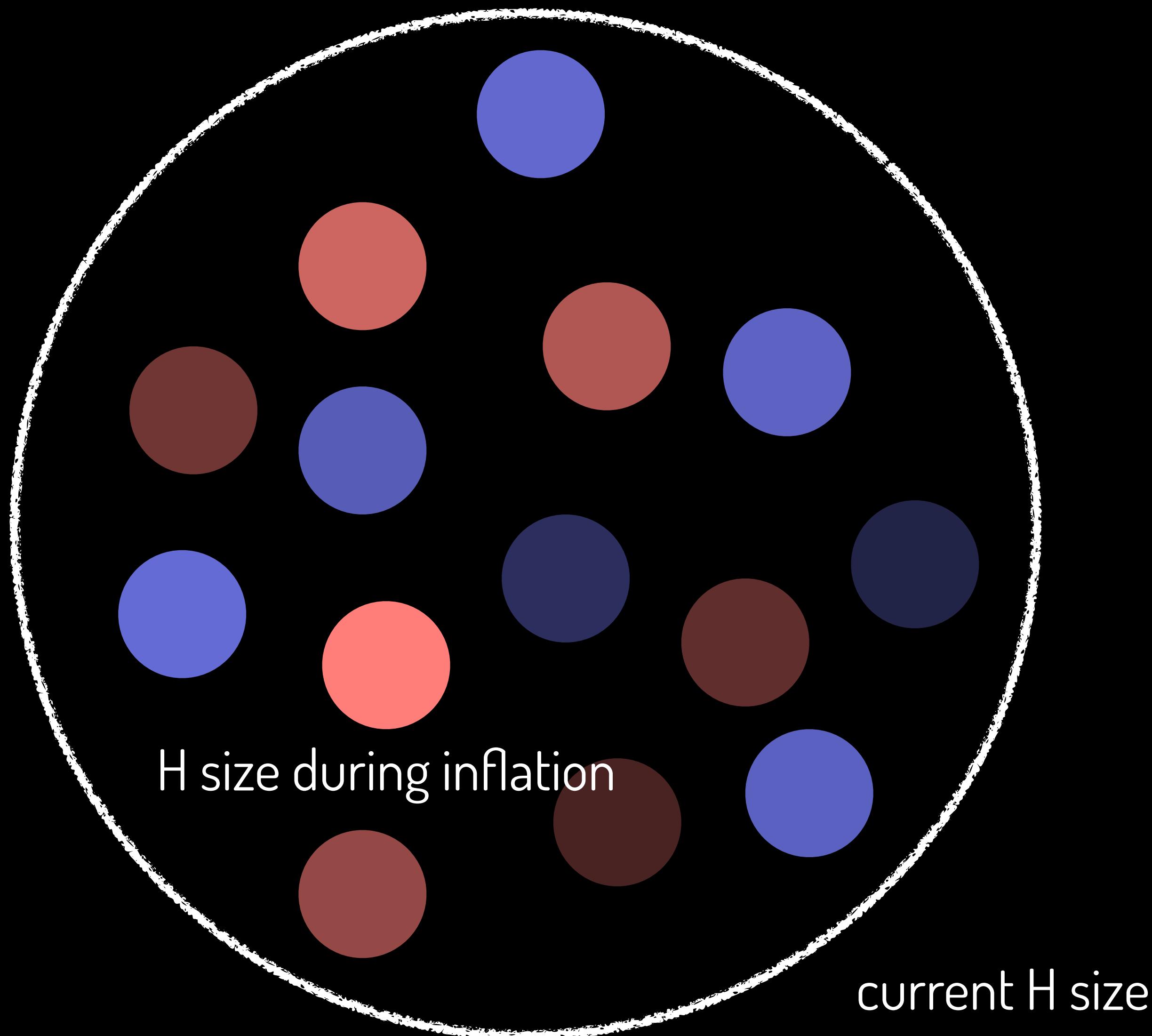


Generation of PTB

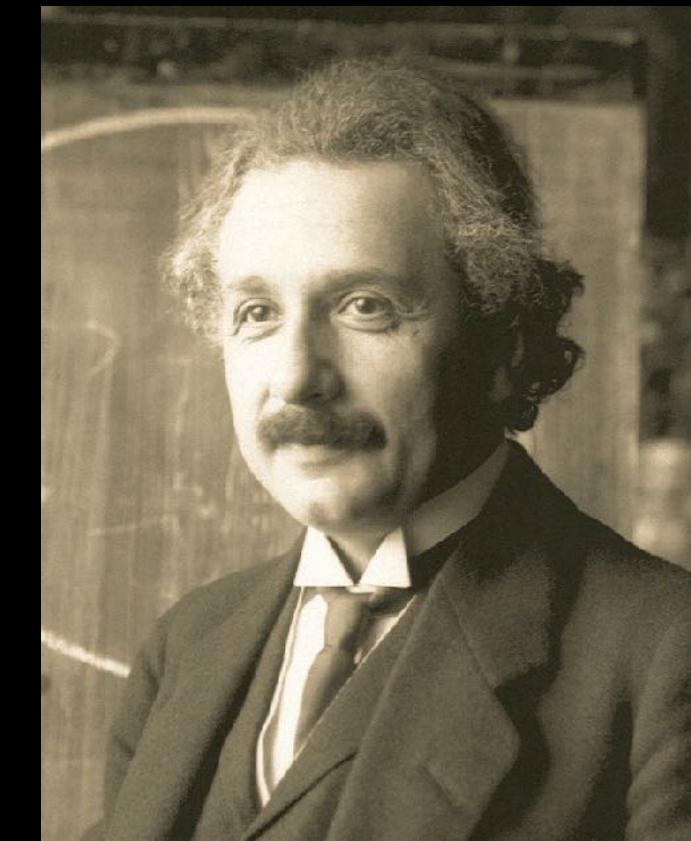
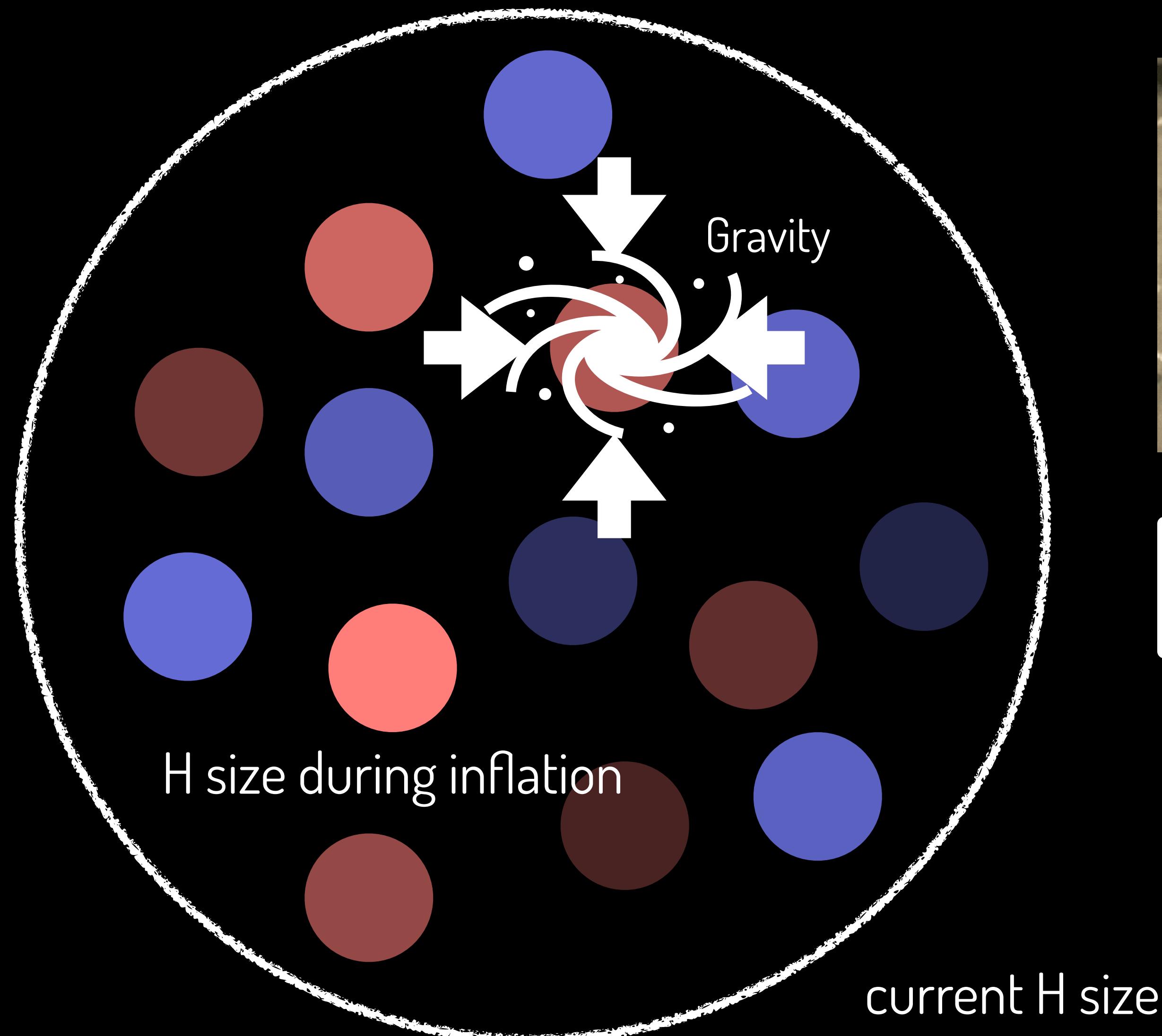


"Horizon" of the expanding U.

Generation of PTB

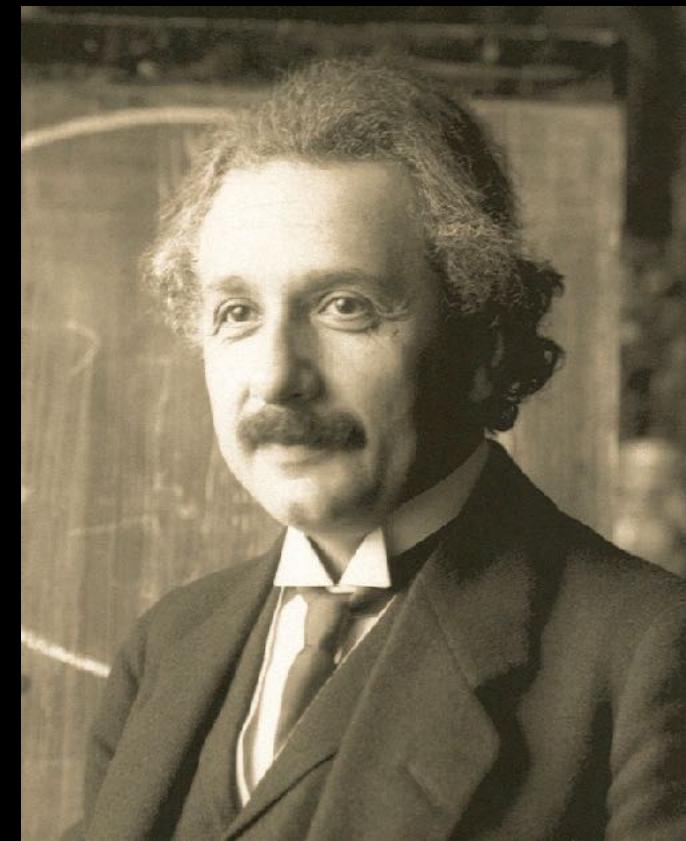
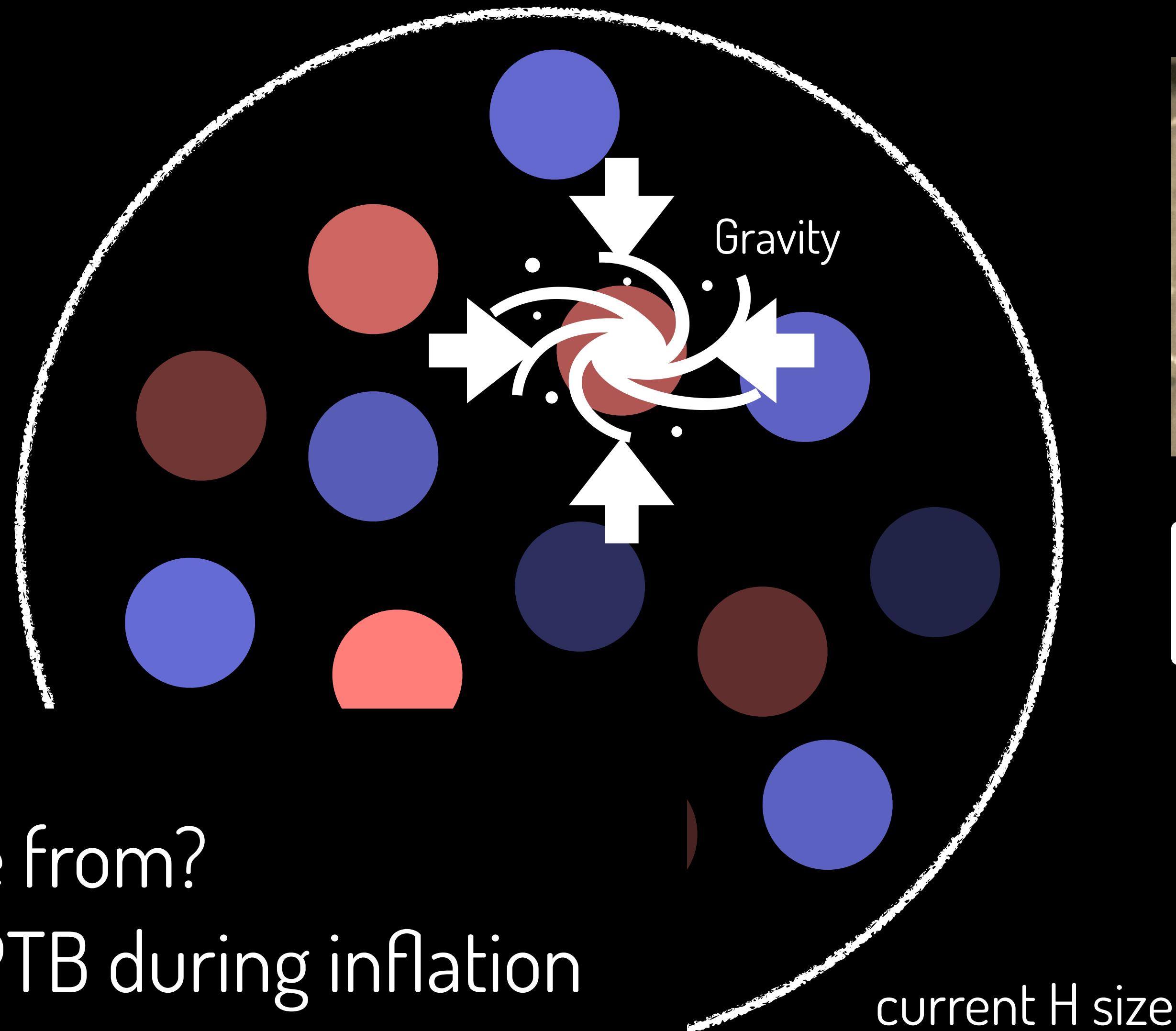


Generation of PTB



Energy = Mass

Generation of PTB

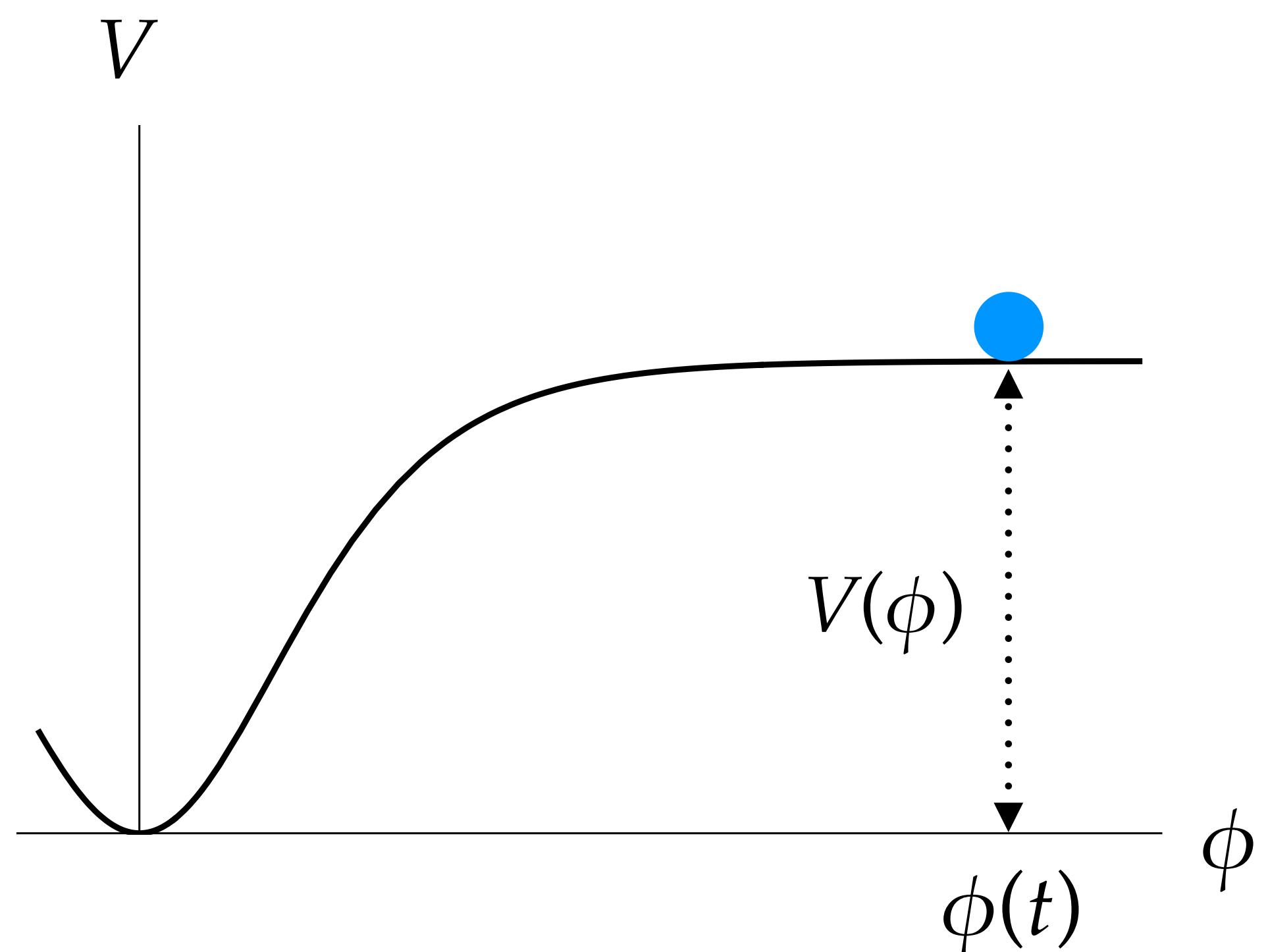


Energy = Mass

Where do we come from?
→ from Quantum PTB during inflation

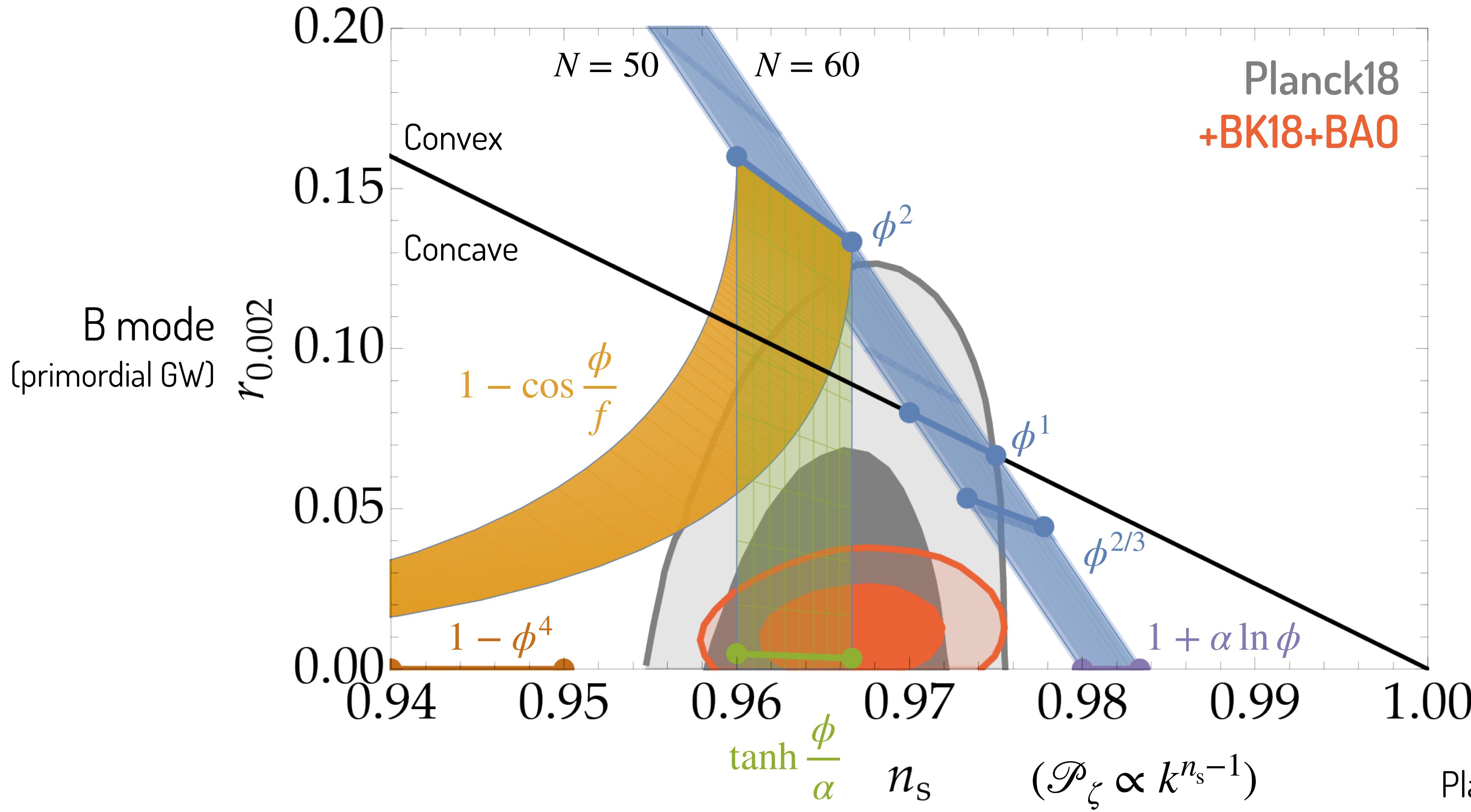
Inflation Theories

Just to realise an Accelerated Expansion (= Dark Energy = almost const. energy), you only need homogeneous VEV of some scalar $\phi(t)$ with the potential $V(\phi)$.

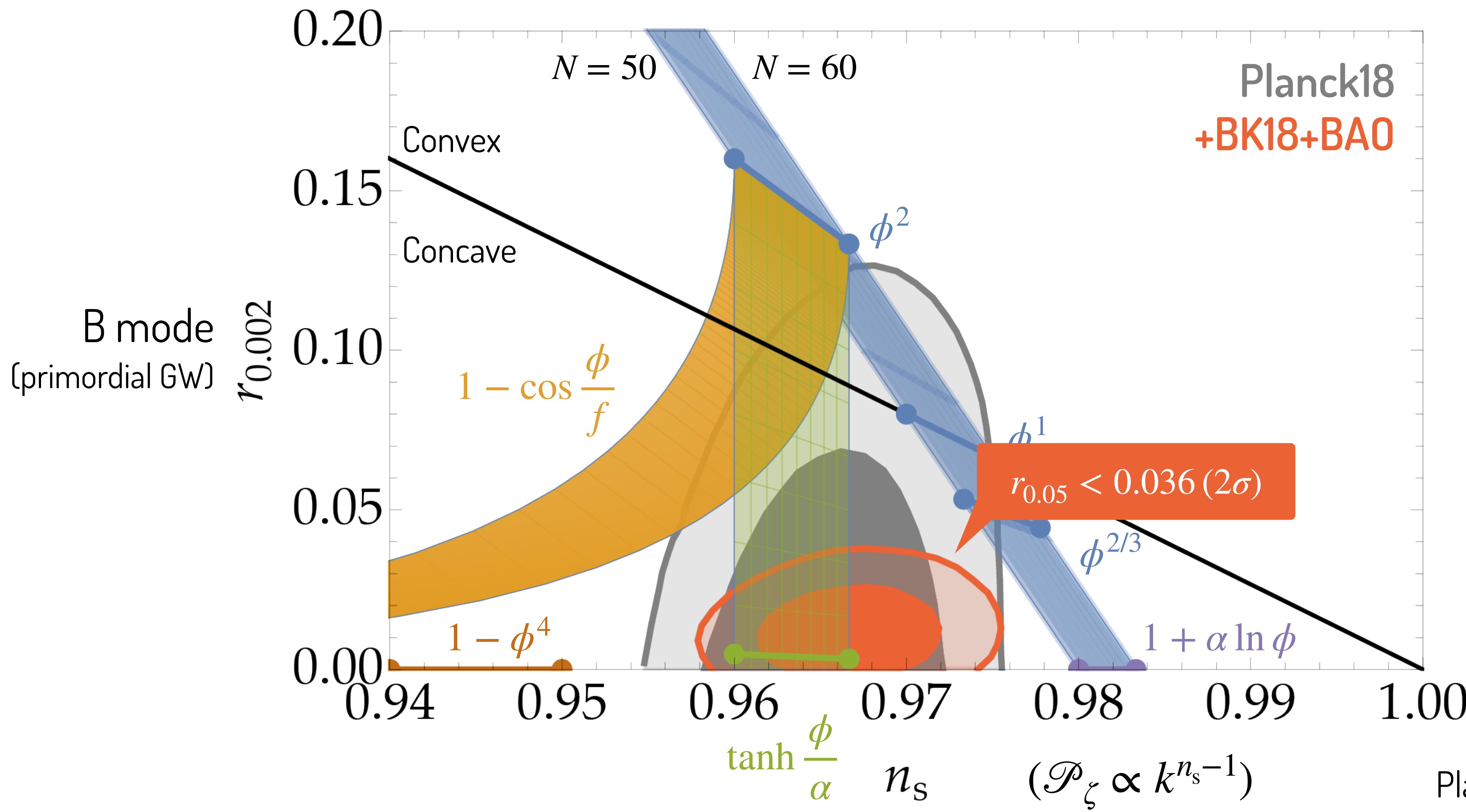


“Inflation of the # of inflation theories”
by T. Matsubara

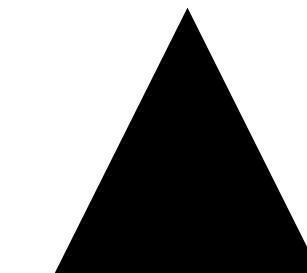
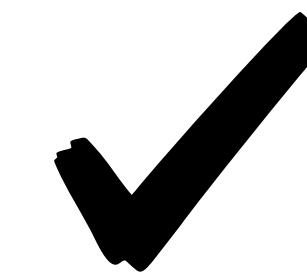
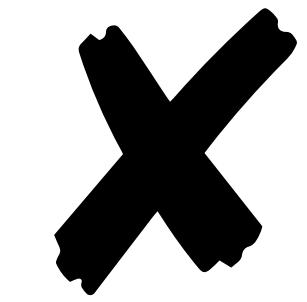
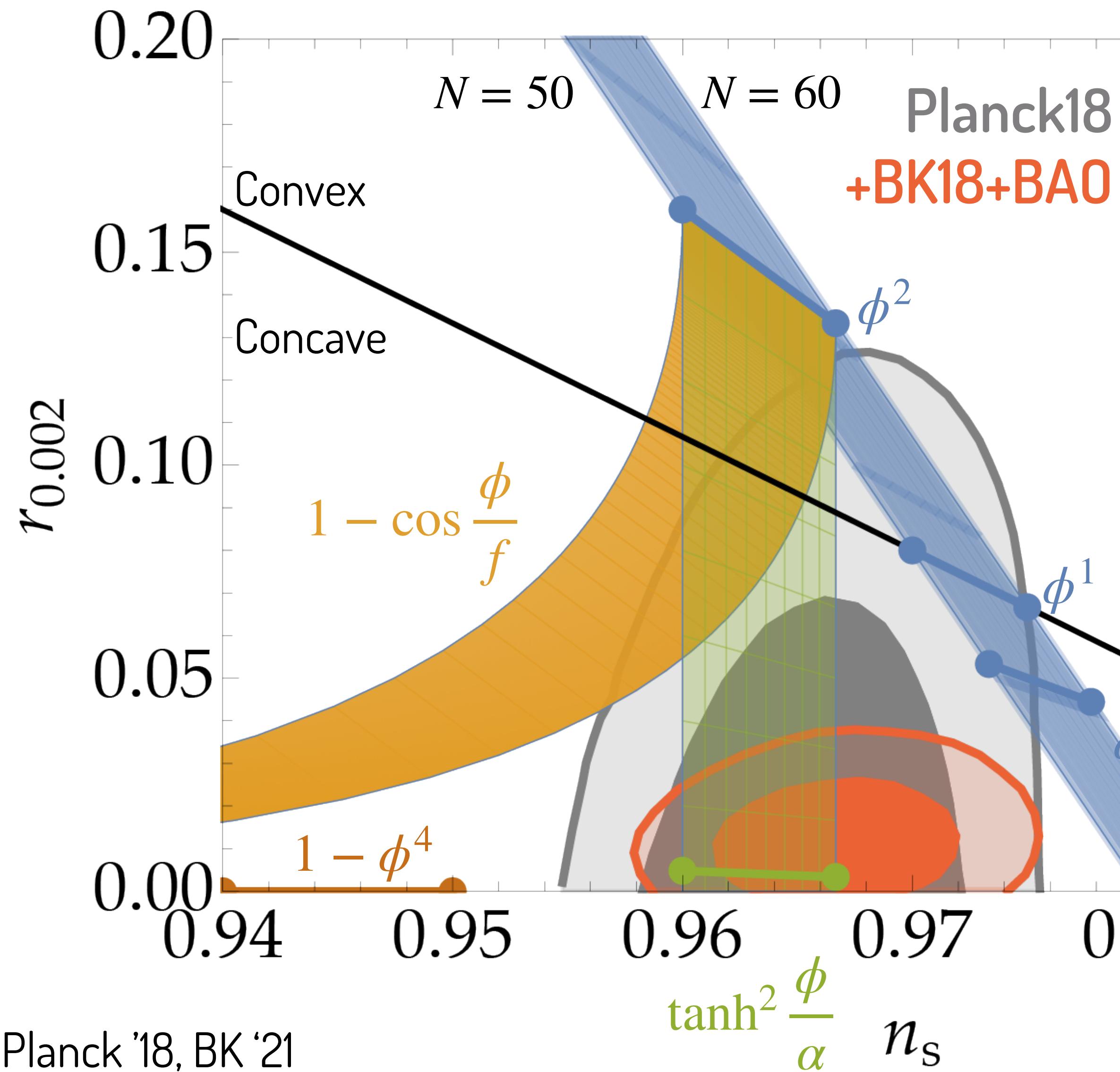
Latest CMB const.



Latest CMB const.



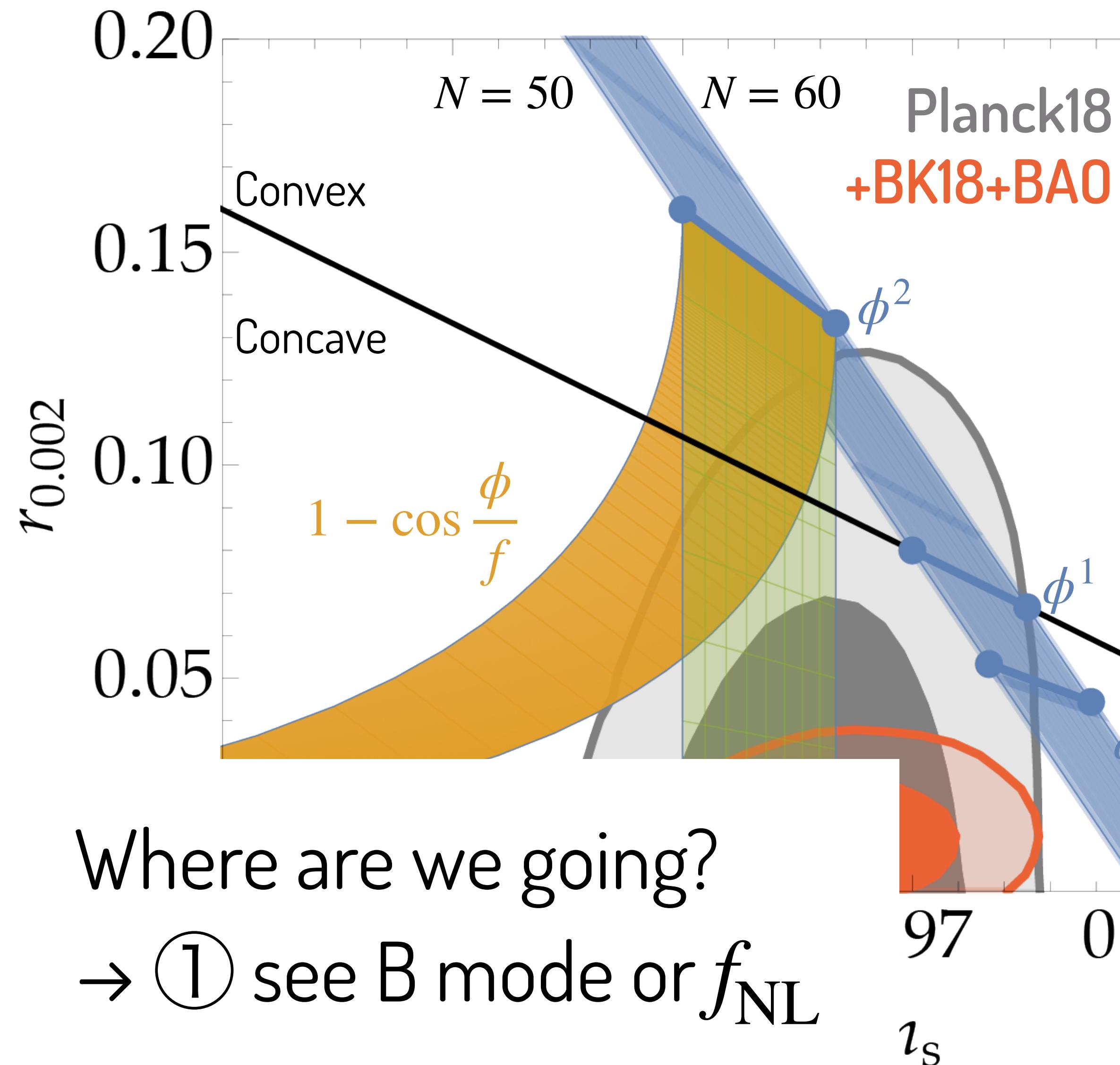
Latest CMB const.



- ▶ Large-field $r \sim \mathcal{O}(0.1)$
 - **chaotic** - **natural**
- ▶ Plateau-type $r \sim \mathcal{O}(10^{-3})$
 - **Starobinsky**
 - **Higgs**

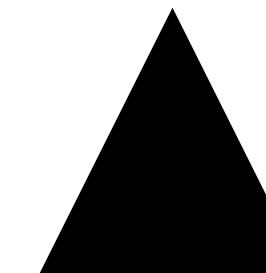
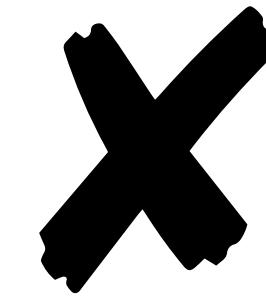
cf. LiteBIRD...
- ▶ Small-field $r \ll 1$
 - **hilltop**
 - c.f. $1 - \phi^4 - \phi - \dots$
- (✓ - curvaton
check nonGauss $f_{NL} \sim \mathcal{O}(1)$

Latest CMB const.



Where are we going?

→ ① see B mode or f_{NL}



- ▶ Large-field $r \sim \mathcal{O}(0.1)$
 - **chaotic** - **natural**
- ▶ Plateau-type $r \sim \mathcal{O}(10^{-3})$
 - **Starobinsky** cf. LiteBIRD...
- $\mathcal{L} = \frac{1}{16\pi G} R + \alpha R^2$
- **Higgs**
- $\mathcal{L} = \left(\frac{1}{16\pi G} + \xi \mathcal{H}^2 \right) R + \mathcal{L}_{\text{SM}}$
- ▶ Small-field $r \ll 1$
 - **hilltop**
 - c.f. $1 - \phi^4 - \phi - \dots$
- (- curvaton
check nonGauss $f_{\text{NL}} \sim \mathcal{O}(1)$)

Other Info?

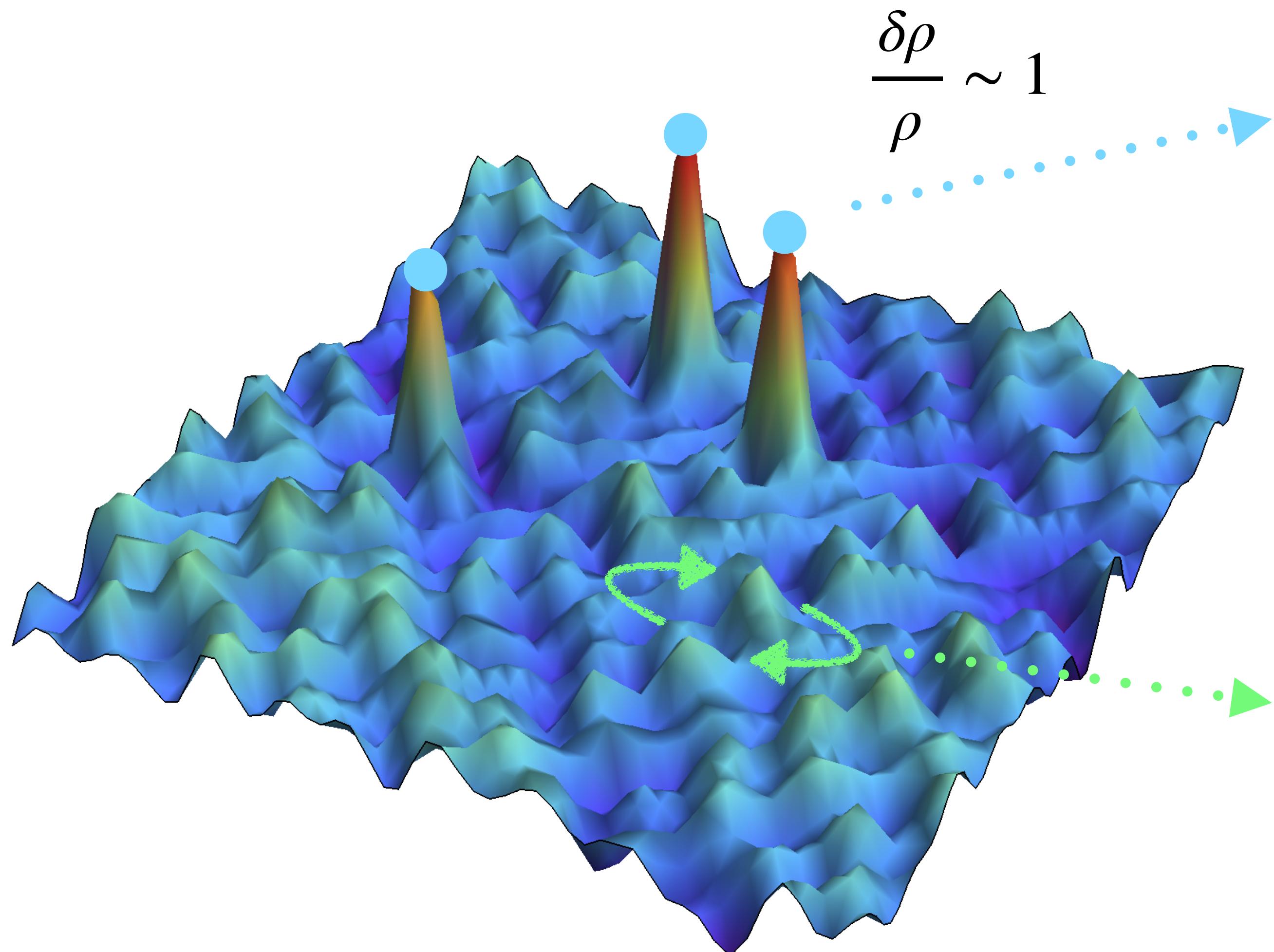


CMB $\gtrsim 1$ Mpc

→ How about smaller scales?

If perturbations get enhanced on small scales...

Large P on small scale

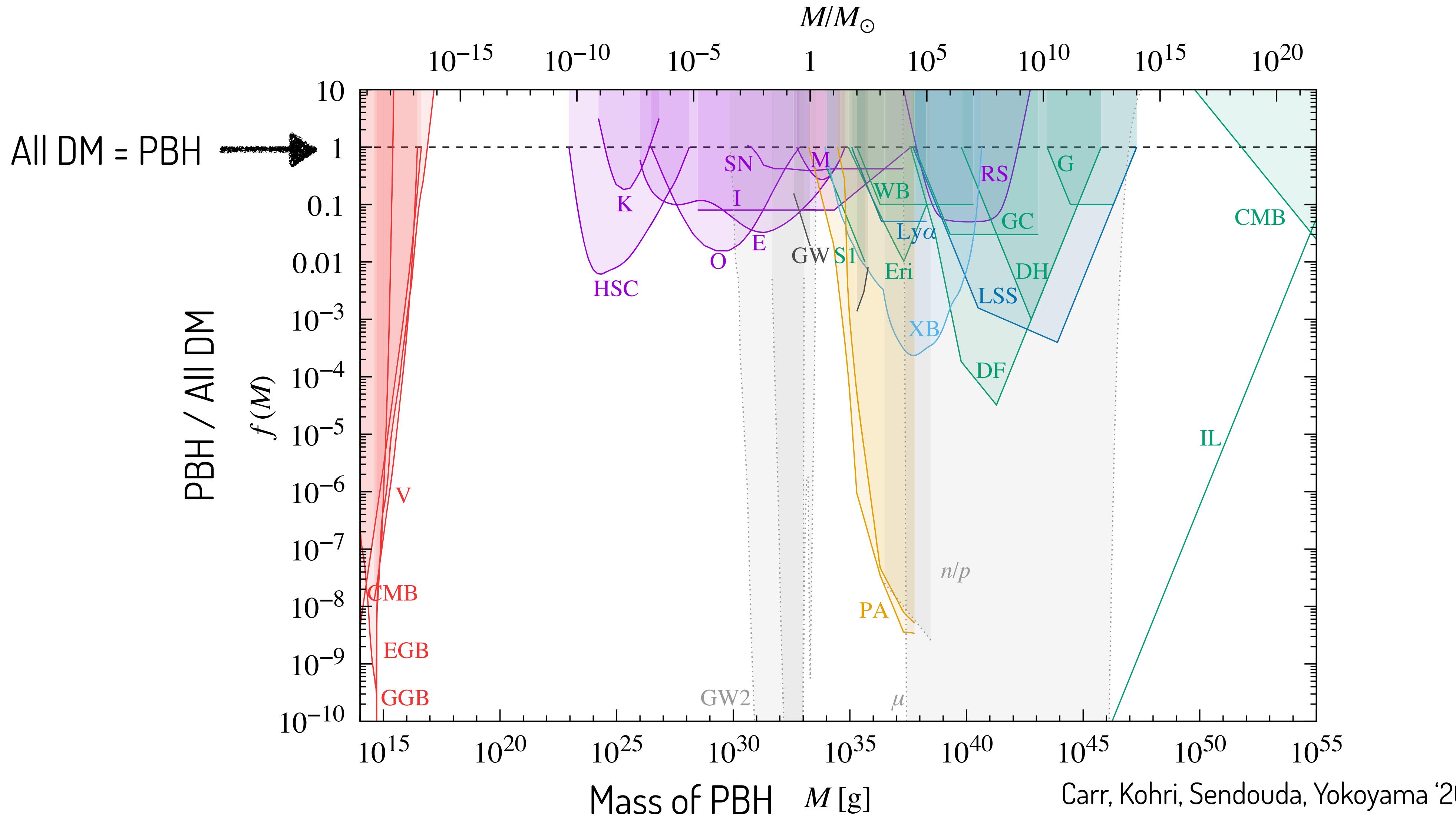


- ❖ Primordial Black Holes
 - Large PTB directly form BHs in RD era before star formation
 - Candidate of Dark Matter

- ↑ Indirect Evidence

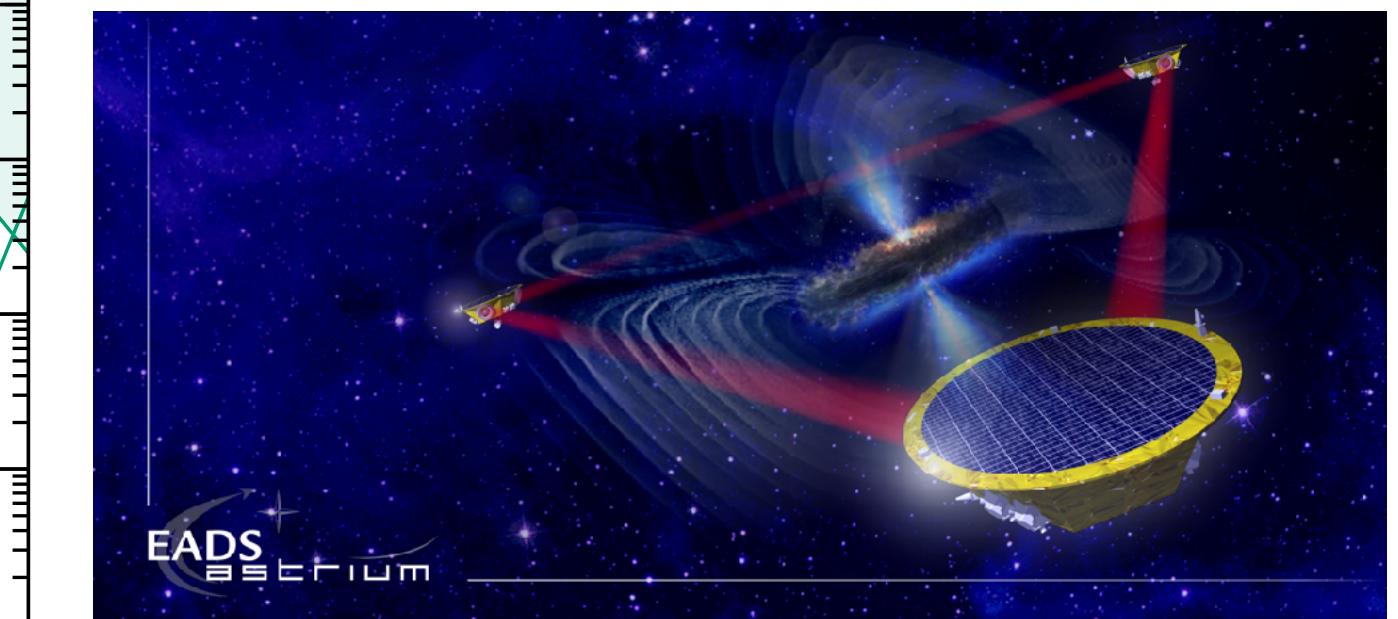
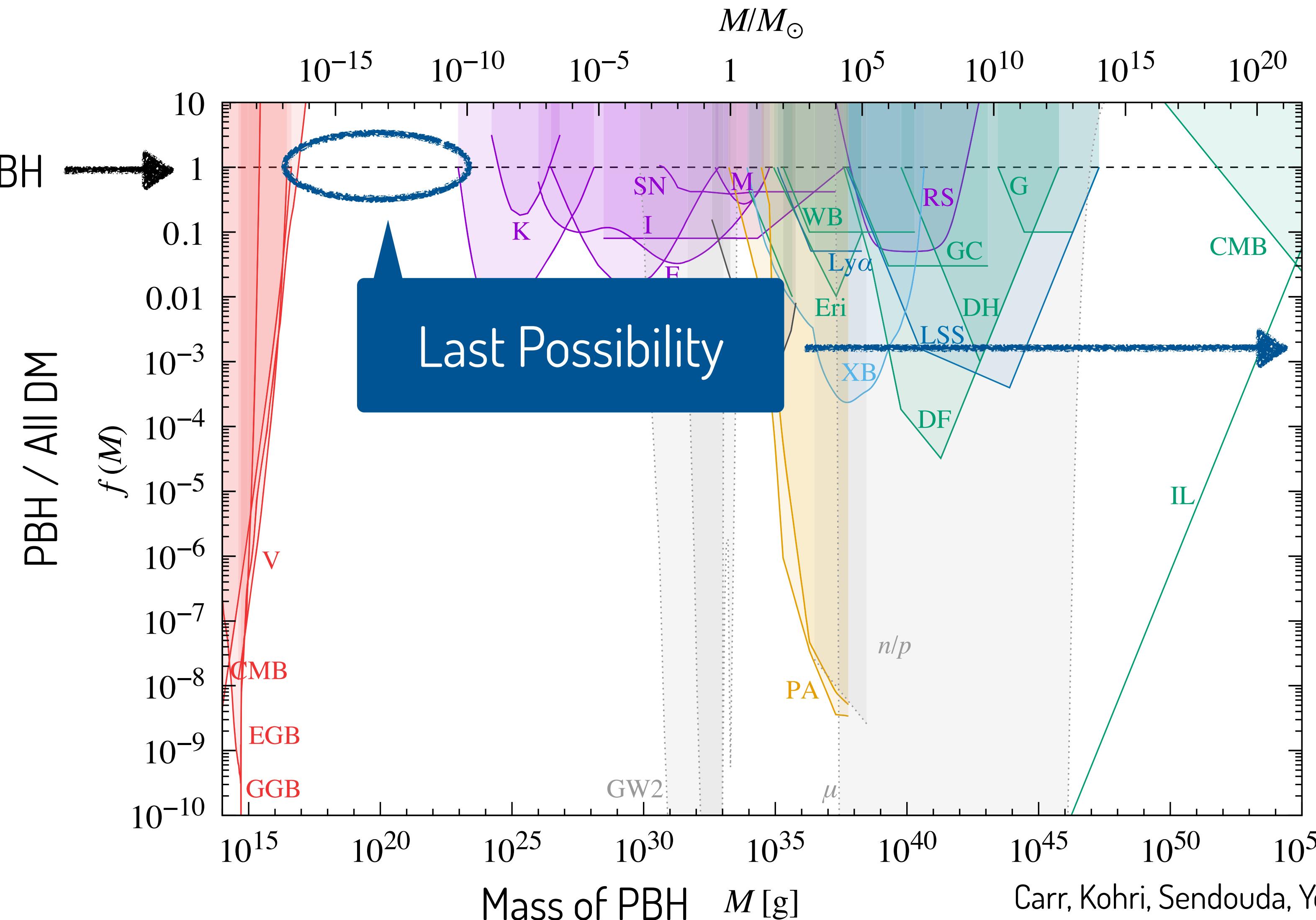
- ❖ Induced Gravitational Waves
 - Stochastic GW b.g. from insufficient PTB for PBH

Obs. Const. on PBH



Obs. Const. on PBH

All DM = PBH

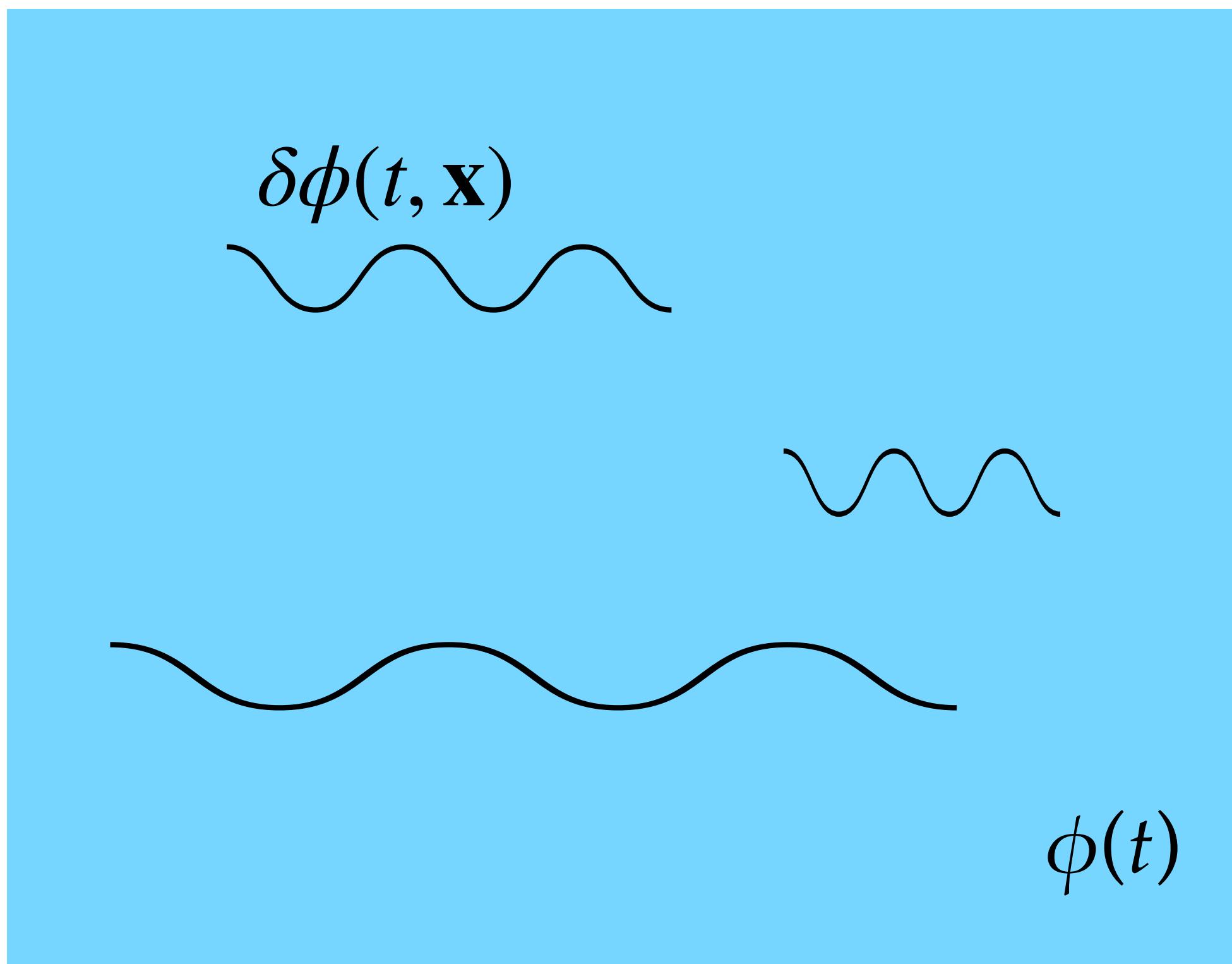


Freq. of corresponding GWs
are at the sweet spot of
LISA (2037–)!

prove PBH to be / not to be
all DM?

How to enhance PTB?

curv. PTB & δN formalism

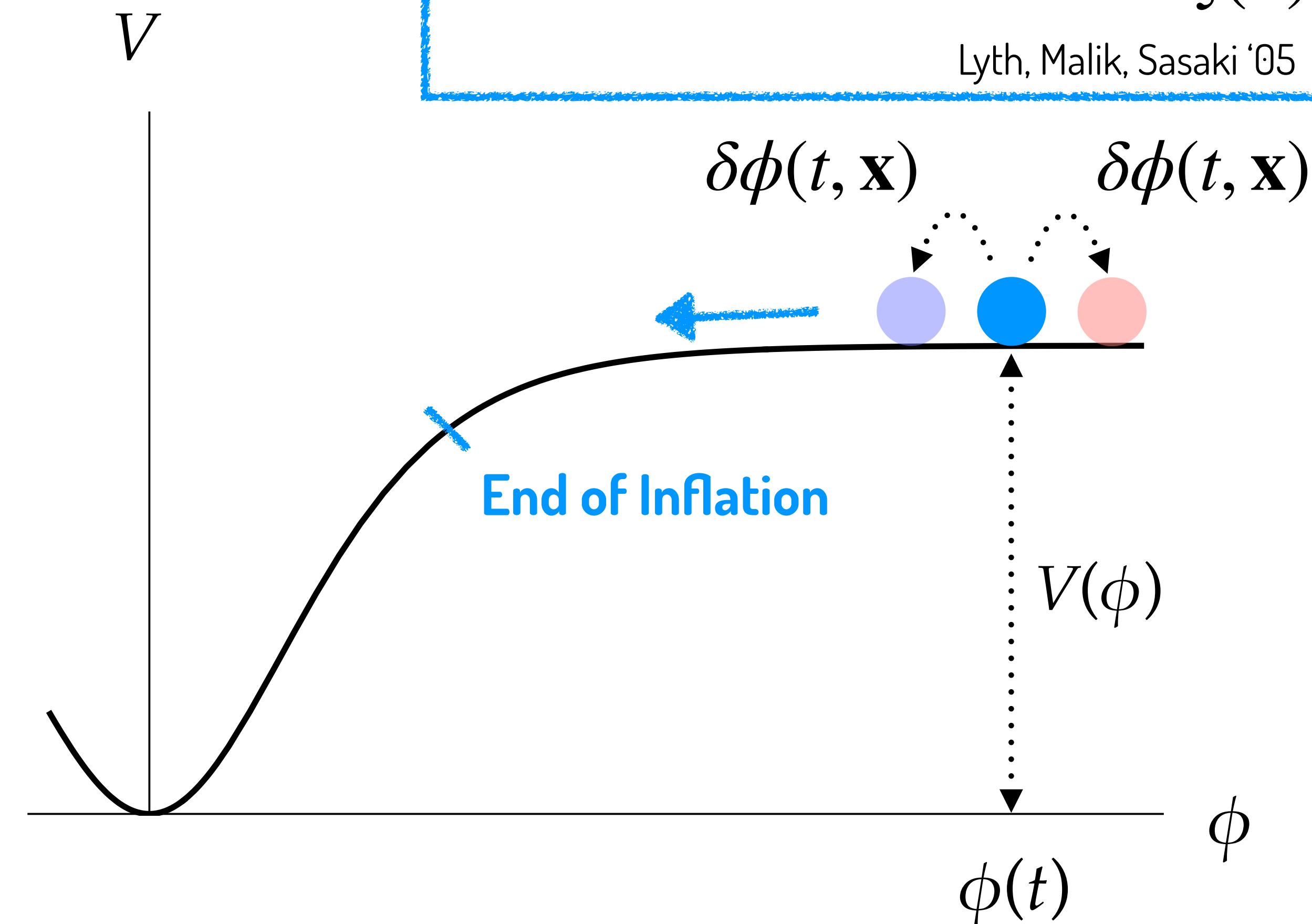


PTB in duration of inflation

$$\delta N = H\delta t \simeq -H \frac{\delta\phi(t, \mathbf{x})}{\dot{\phi}(t)}$$

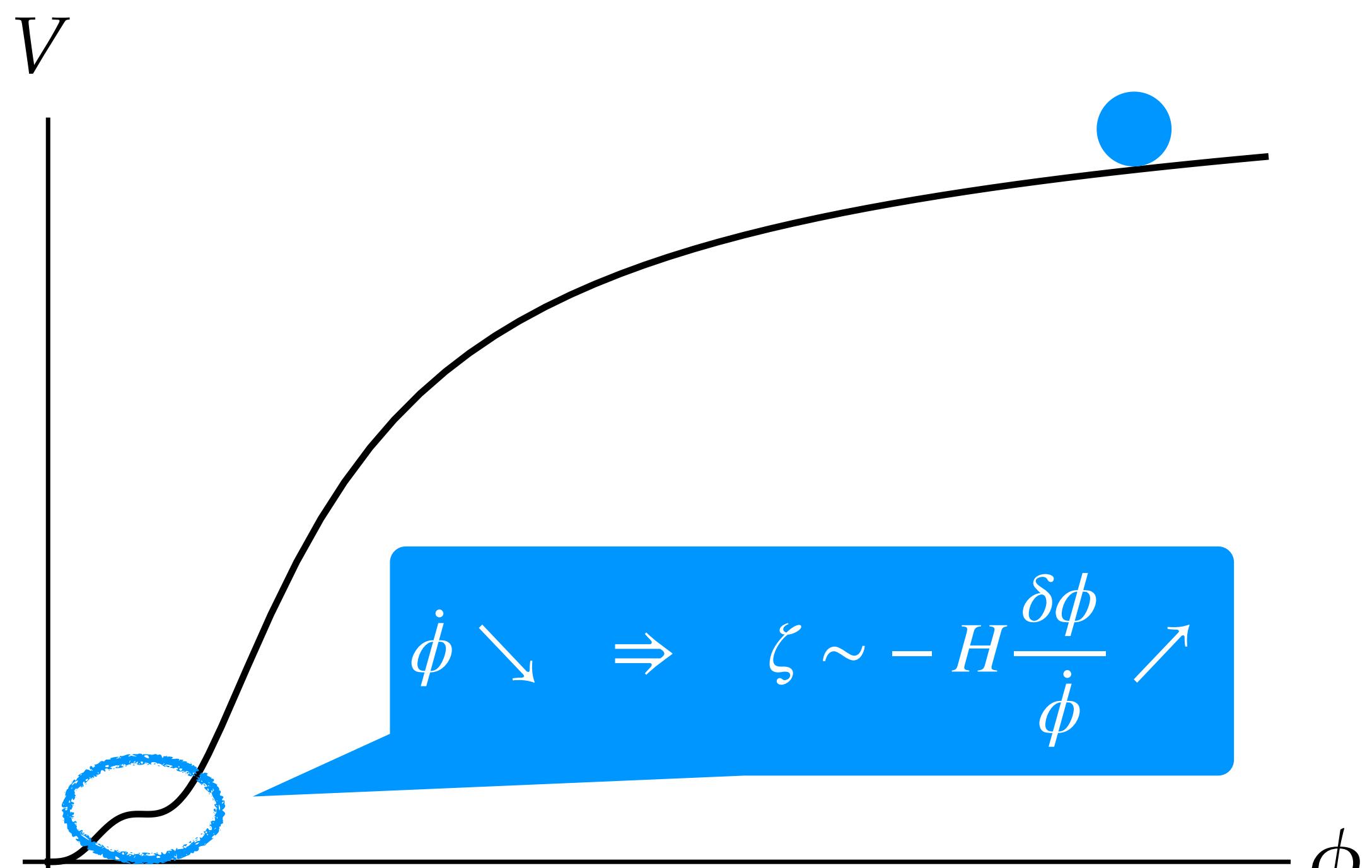
= conserved curv. PTB $\zeta(\mathbf{x})$

Lyth, Malik, Sasaki '05



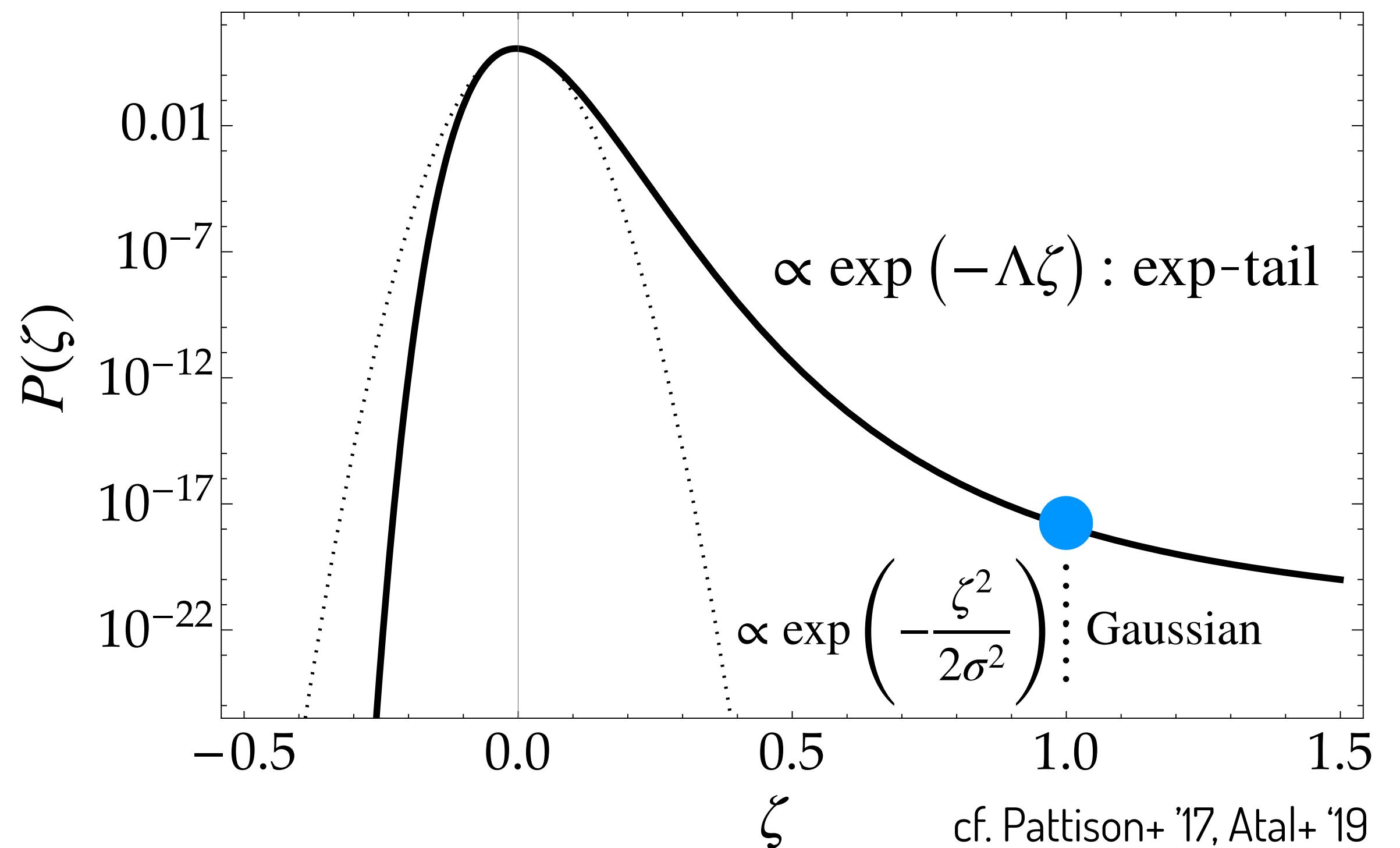
How to enhance PTB?

inflection model & exp-tail



cf. Ezquiaga, Garcia-Bellido, Morales '17

$\dot{\phi}$ is reducing $\rightarrow \delta\phi$'s effect is asymmetric!



$\propto \exp(-\Lambda\zeta)$: exp-tail

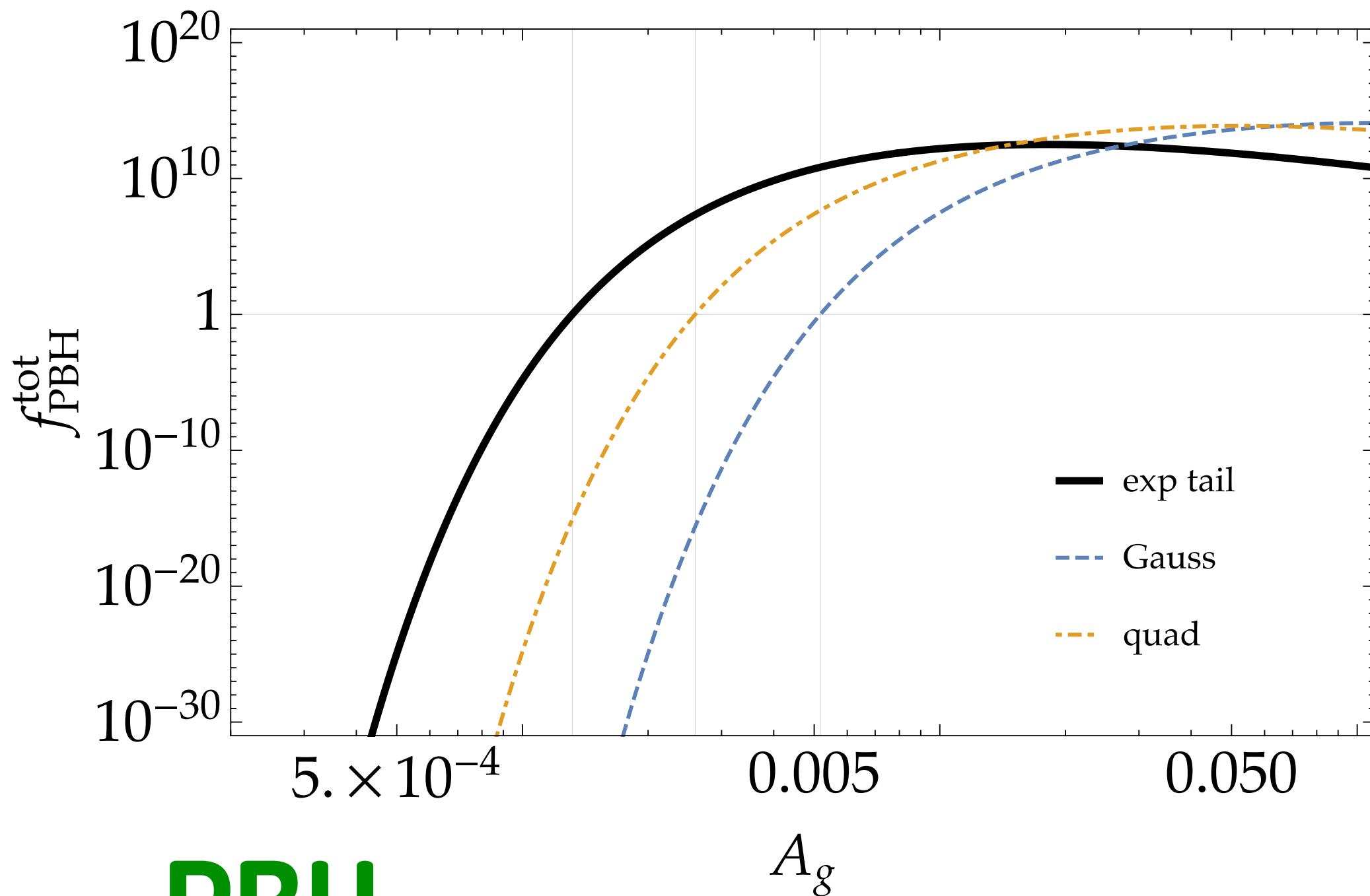
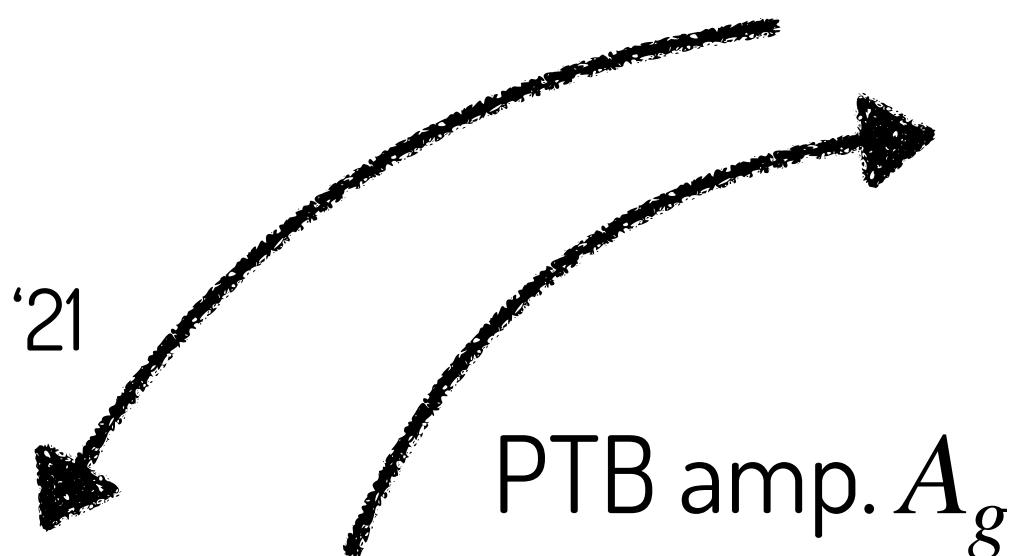
$\propto \exp\left(-\frac{\zeta^2}{2\sigma^2}\right)$: Gaussian

cf. Pattison+ '17, Atal+ '19

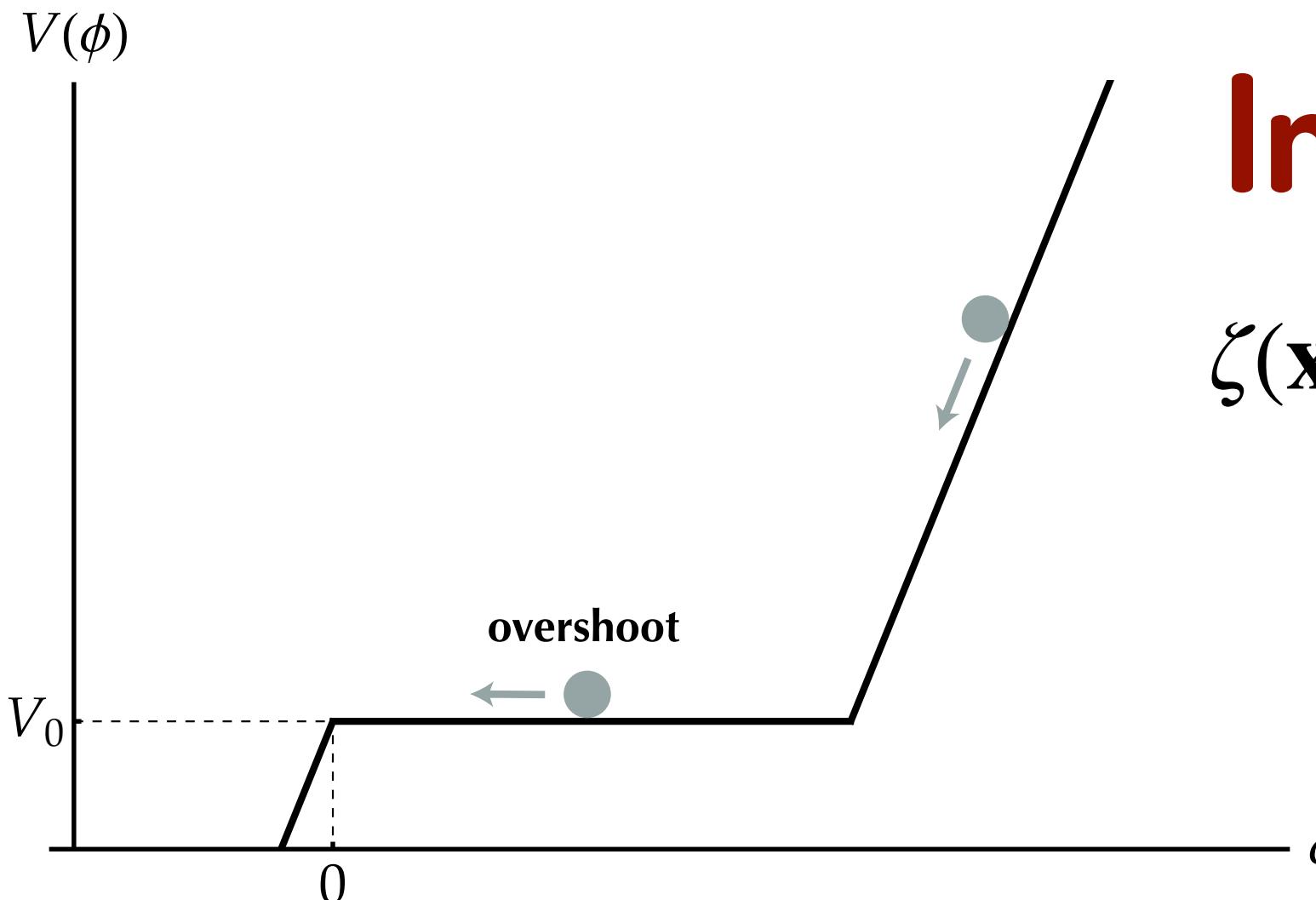
$\delta\phi \rightarrow \zeta = \delta N$: non-linear relation

Triangle Study

“Peak Theory”
Statistical Estimation
Yoo+ '18, '19, '20
Kitajima, YT, Yokoyama, Yoo '21



PBH

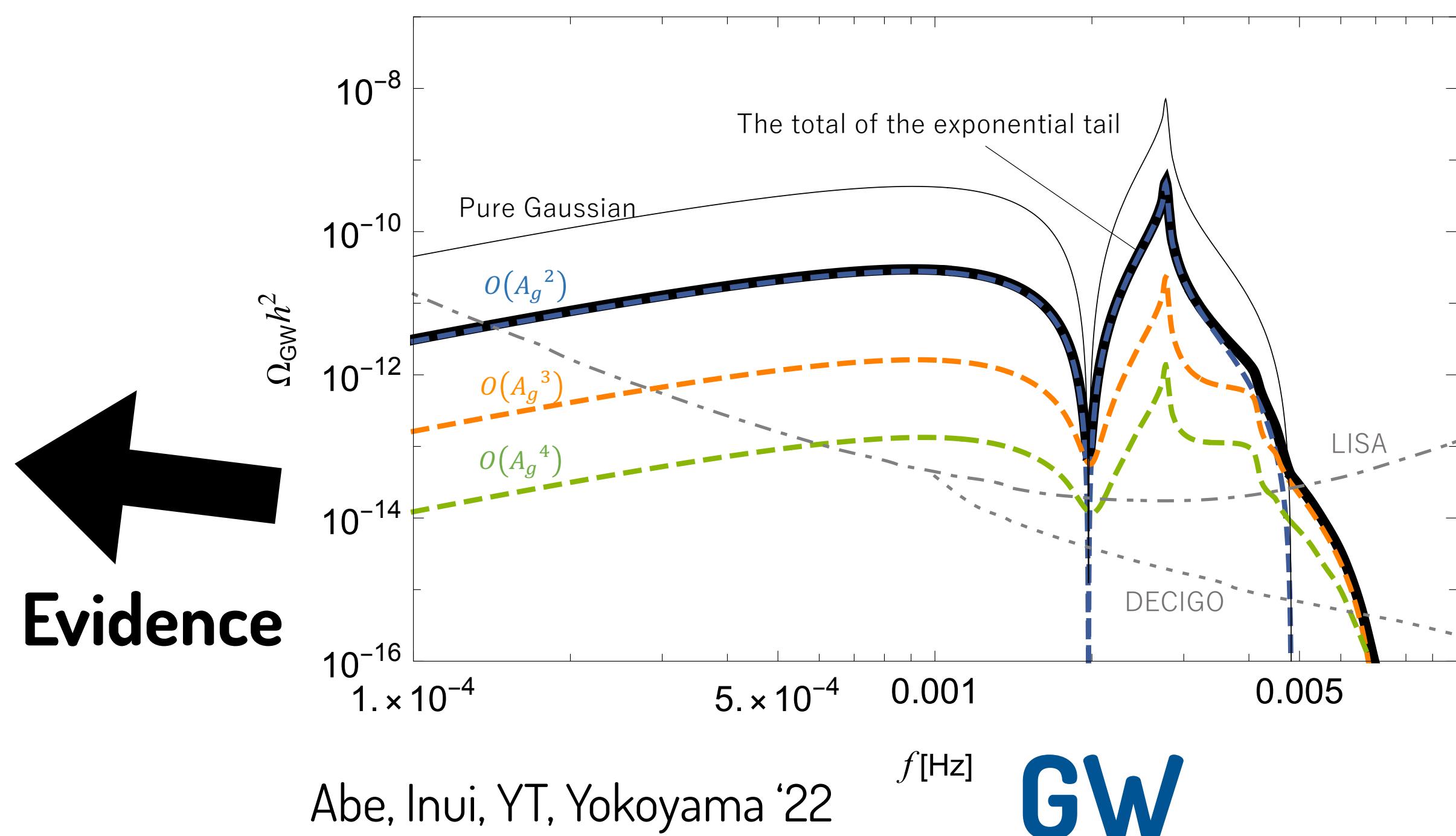


Inflation

$$\zeta(\mathbf{x}) = -\frac{1}{3} \ln(1 - 3\zeta_G(\mathbf{x}))$$

Cai+ '18

perturbative GR



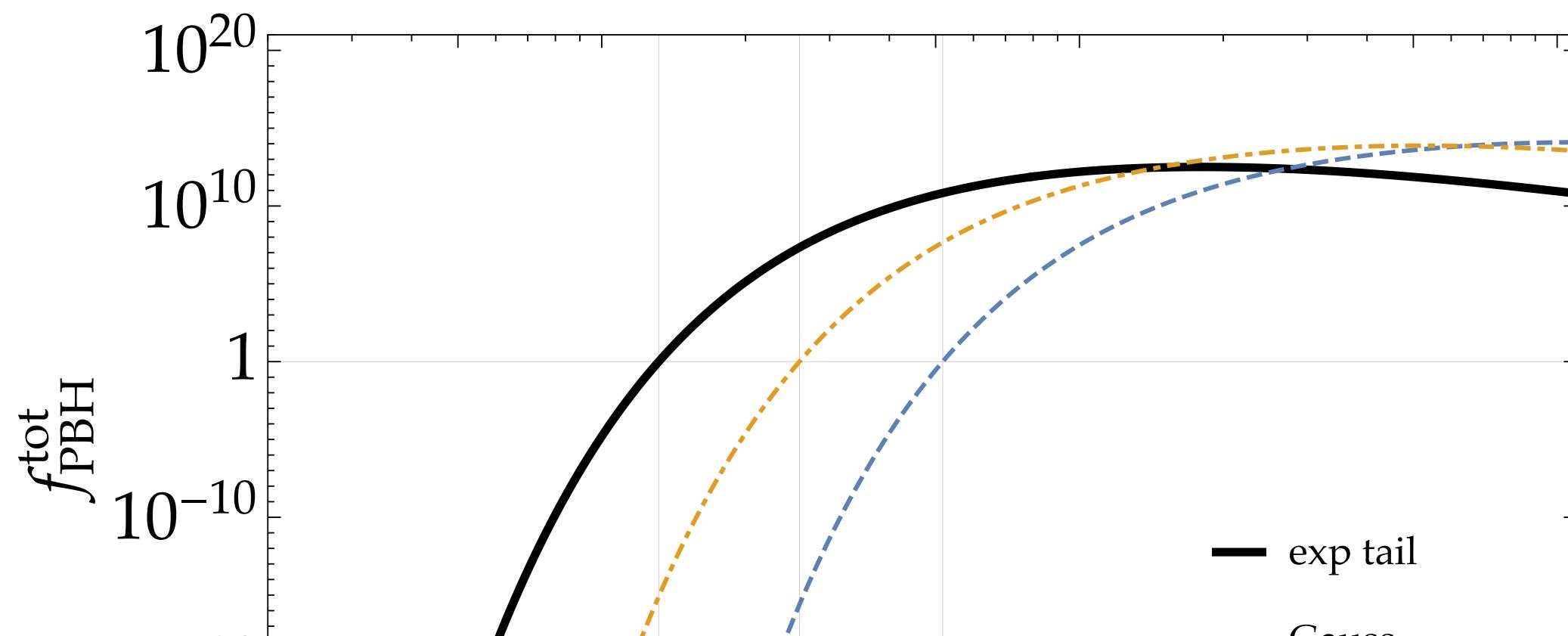
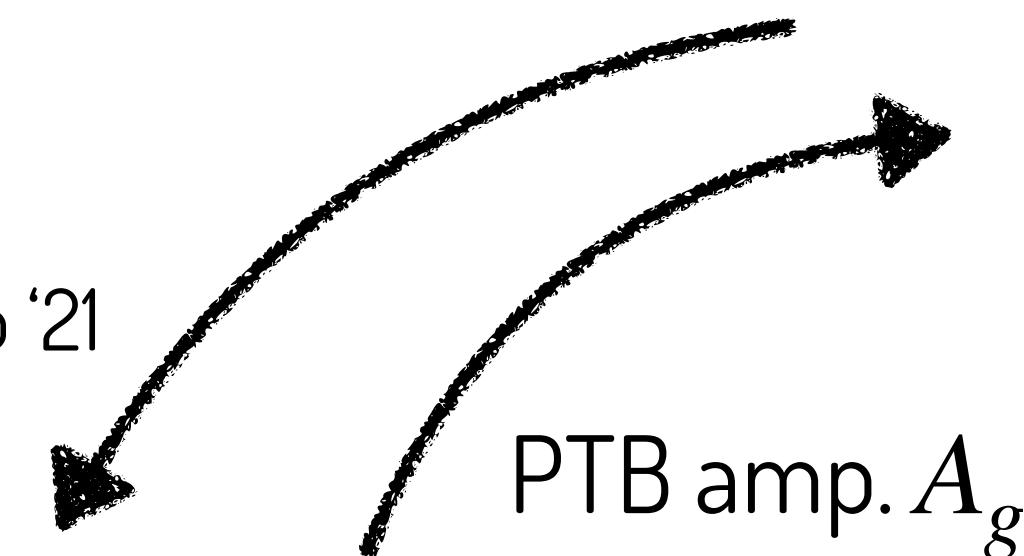
Evidence

Abe, Inui, YT, Yokoyama '22

GW

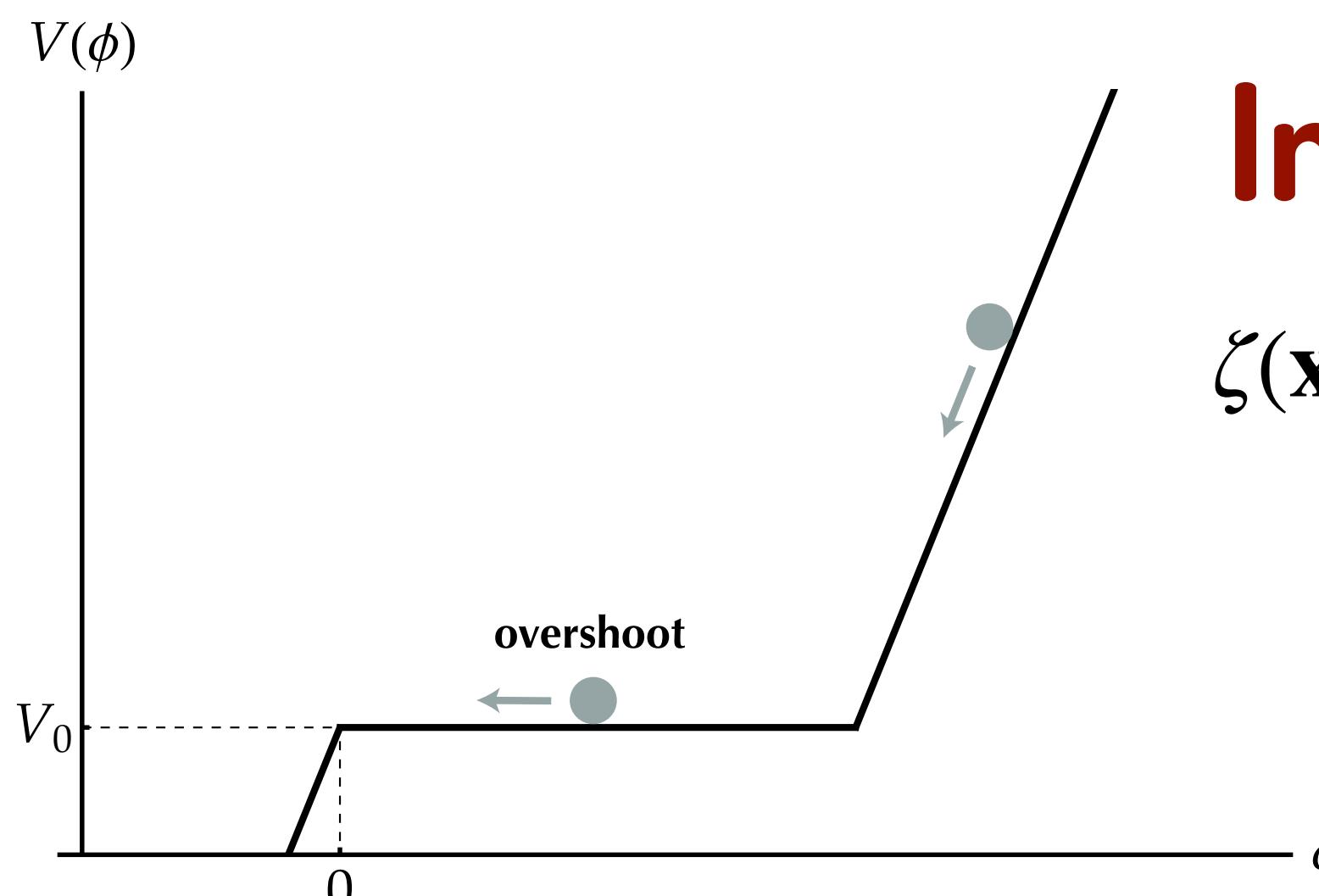
Triangle Study

“Peak Theory”
Statistical Estimation
Yoo+ '18, '19, '20
Kitajima, YT, Yokoyama, Yoo '21



Where are we going?

→ ② triangle study for a rigorous (dis)proof of PBH-DM

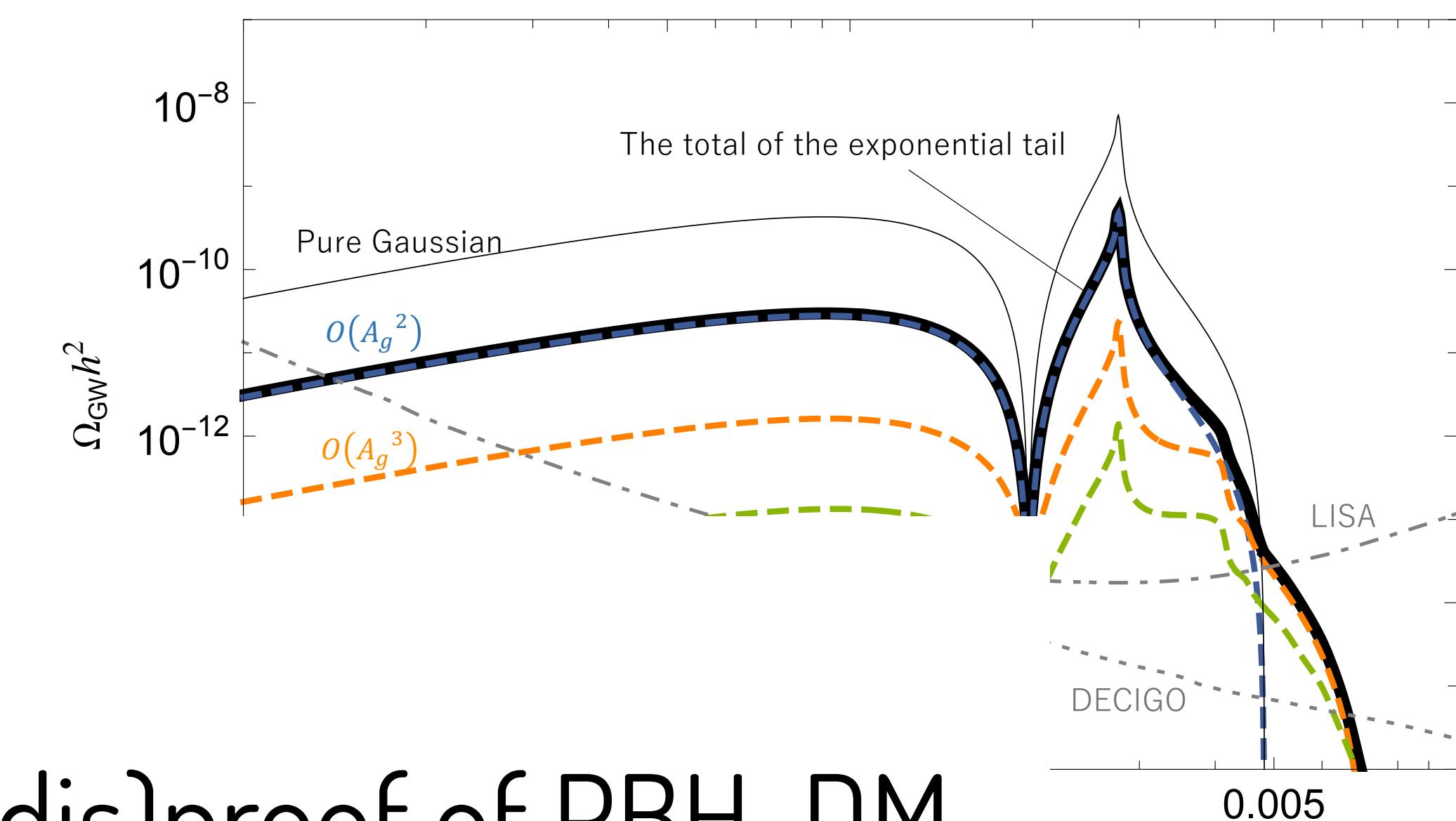


Inflation

$$\zeta(\mathbf{x}) = -\frac{1}{3} \ln(1 - 3\zeta_G(\mathbf{x}))$$

Cai+ '18

perturbative GR



W

Conclusions

Where do we come from?

From quantum perturbations during inflation.

Where are we going?

- ① see B mode or f_{NL} (after that ... ?)
- ② triangle analysis (Inflation \leftrightarrow PBH \leftrightarrow Gw) toward PBH-DM

(see our review 2211.05767 Escrivà, Kuhnel, YT as invited book chapter in
"Listening to the dark Universe: black holes in the era of gravitational-wave astronomy")