IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Early Universe Cosmology

future prospects from a personal perspective

Misao Sasaki

December 18, 2024

my encounters with Hitoshi

- My first encounter with Hitoshi was perhaps around 2010.

Hongkong, May 2011

- Sometime later at a workshop at IPMU, we drank heavily. Next day I had a terrible hangover, but Hitoshi looked perfectly fine!

➢ When he applied for a big JSPS grant "Why does the Universe accelerate?", which was eventually approved, he kindly invited me to join, and made me PI of the project group on inflation. It was completed with great success.

Organizing this small workshop was made possible thanks to the grant, which led to the paper below.

PRL **117,** 061101 (2016) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2016

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

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(Received 3 April 2016; published 2 August 2016)

We point out that the gravitational-wave event GW150914 observed by the LIGO detectors can be explained by the coalescence of primordial black holes (PBHs). It is found that the expected PBH merger rate would exceed the rate estimated by the LIGO Scientific Collaboration and the Virgo Collaboration if

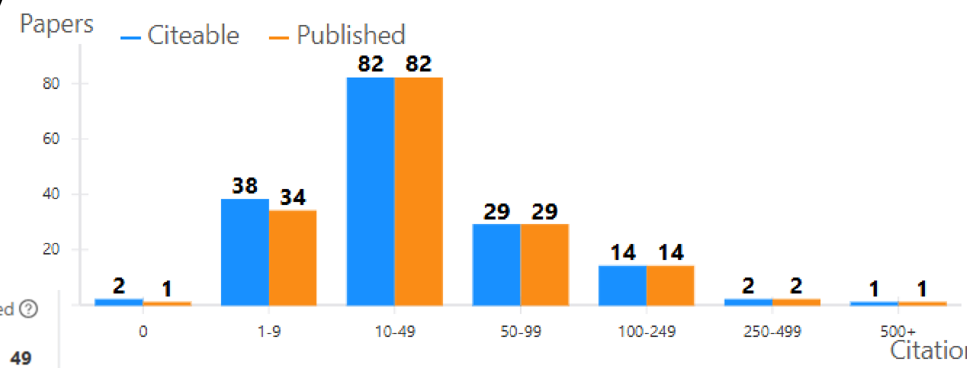
- Project group’s total number of publications =168, with total citation = 8024

Citation Summary

in 5 years

☐ Exclude self-citations ⓘ

	Citeable ⓘ	Published ⓘ
Papers	168	163
Citations	8,024	8,018
h-index ⓘ	47	47
Citations/paper (avg)	47.8	49.2

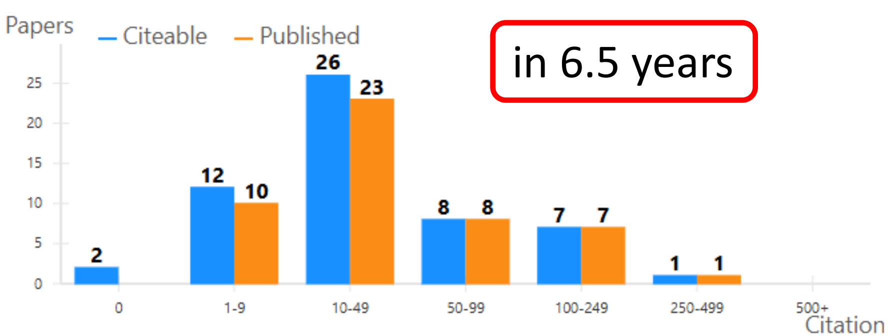


- In 2017, just before my retirement from Kyoto University, Hitoshi offered me a project professor position at IPMU.

- To explain my job at IPMU, he stopped at Kyoto Sta. on his way to somewhere south, and invited me for a couple of drinks. We ended up drinking 5-6 mugs of beer (maybe more…)

	Citeable ⓘ	Published ⓘ
Papers	56	49
Citations	2,582	2,524
h-index ⓘ	24	24
Citations/paper (avg)	46.1	51.5

in 6.5 years

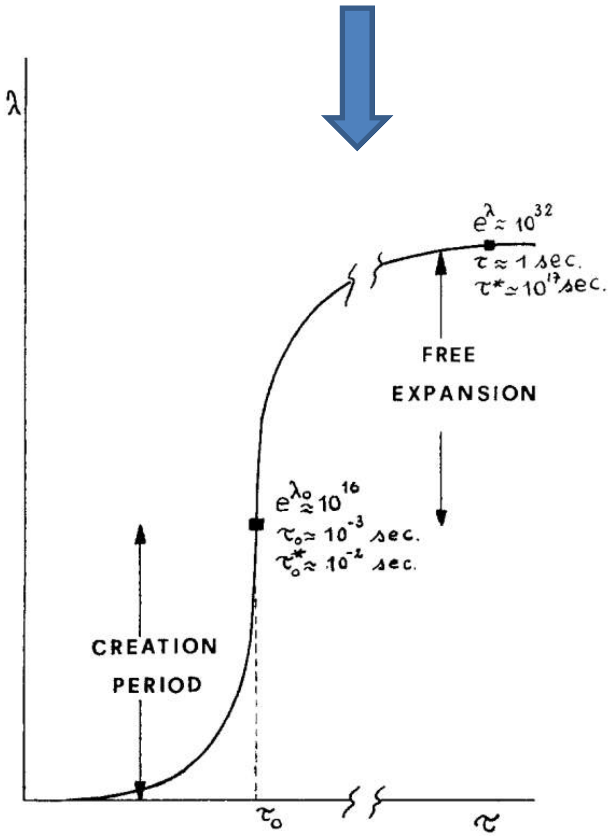


- I joined IPMU in April 2018. Thanks to IPMU’s fantastic research environment, my research activity was enhanced more than ever!

Back to Physics

What happened in the very early Universe?

Brout, Englert & Gunzig ’77, Starobinsky ’79, Guth ’81, Sato ’81, Linde ‘81…



- The Universe experienced a quasi-exponential expansion (inflation) at its very early stage; perhaps at $\rho \gtrsim (10^{15}\mathrm{GeV})^4$.
- It lasted at least 50~60 e-folds ($>10^{30}$).
- Most probably it was driven by a slow-rolling scalar field.

Why Inflation?

- It was meant to solve the initial condition (singularity, horizon & flatness, etc.) problems in Big-Bang Cosmology:

  if any of them can be said to be solved depends on precise definitions of the problems.

- Quantum vacuum fluctuations during inflation turn out to play the most important role. They give the initial condition for all the structures in the Universe.

- Cosmic gravitational wave background is also generated.

more on ∨ inflation
the meaning of

1. Homogeneity and isotropy are the (most important) assumption, NOT a consequence of inflation.

2. Quasi-exponential expansion in the “Einstein frame”: conformal invariant definition.

3. At least 50-60 e-folds before the end of inflation: solving “horizon problem”

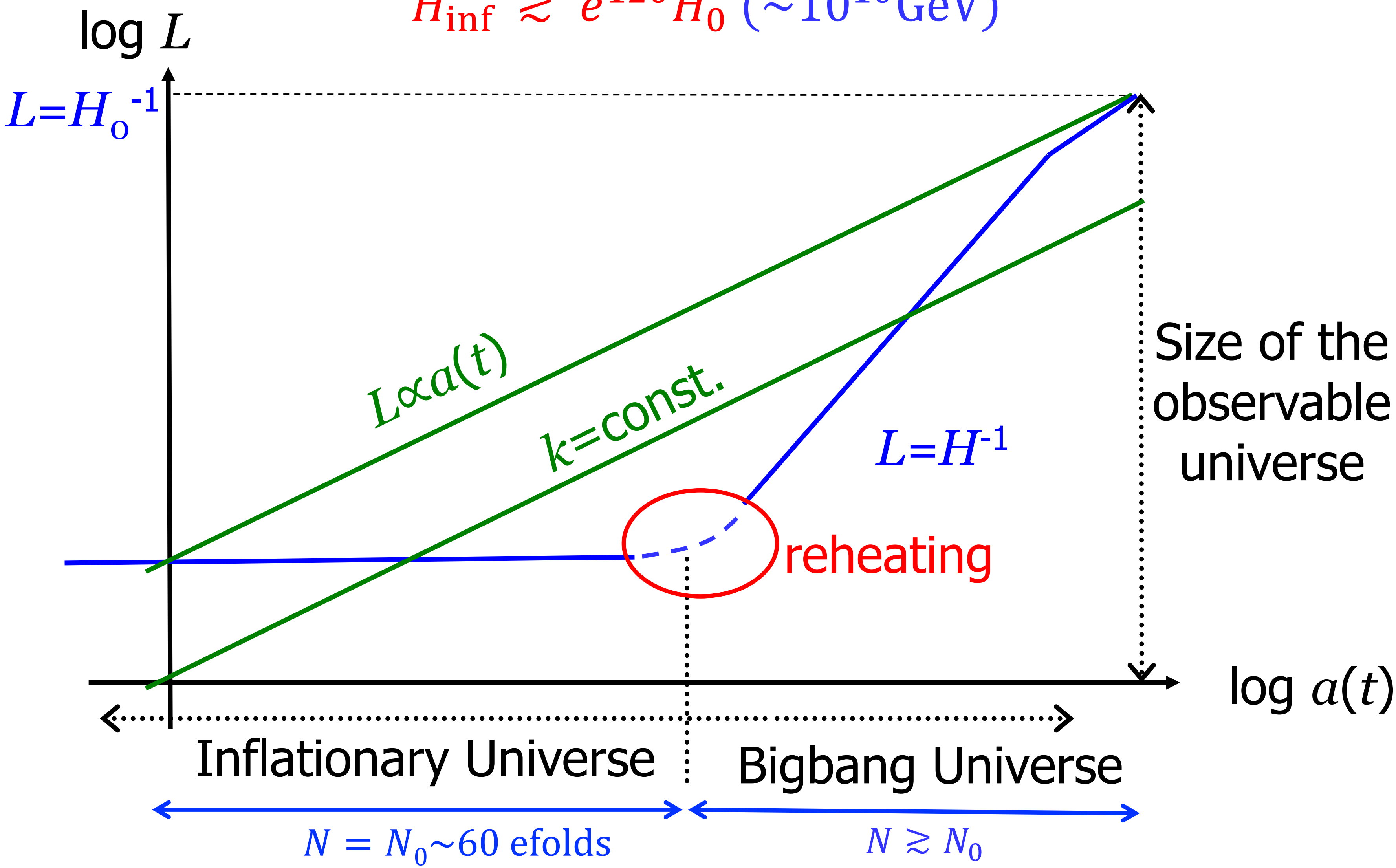
4. Don’t care what happened before inflation: predictions are almost independent of initial conditions.

1 & 2: basic assumptions/definition of inflation

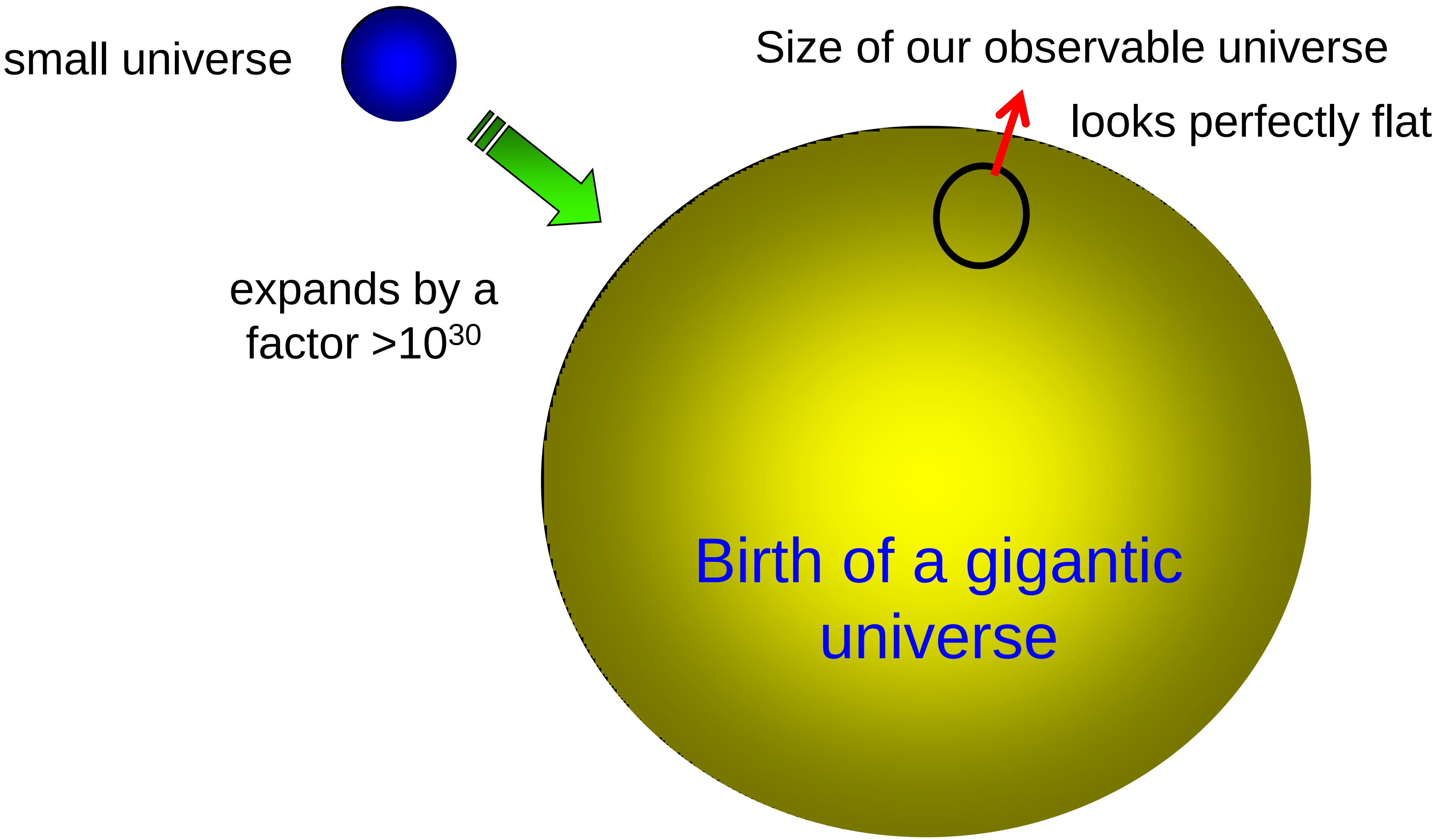
Kinematics

length scales of the inflationary universe

$$H_{\rm inf} \gtrsim e^{120} H_0 \; (\sim 10^{10}\,\mathrm{GeV})$$



Flatness



Flatness can be explained by Inflation

NB: Inflation may not always imply flatness

Dynamics

Seed of cosmological perturbations

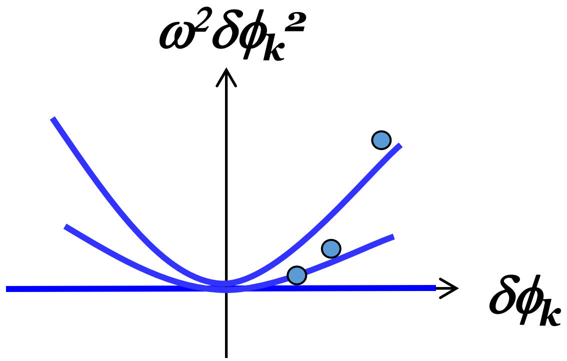
Mukhanov & Chibisov '81, ….

Zero-point (vacuum) fluctuations of ϕ: $\delta\phi = \sum_k \delta\phi_k(t) e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$

$$\delta\ddot{\phi}_k + 3H\delta\dot{\phi}_k + \omega^2(t)\delta\phi_k = 0; \quad \omega^2(t) = \frac{k^2}{a^2(t)}$$

rapidly decreases

harmonic oscillator with friction term and time-dependent ω



$\delta\phi_k \rightarrow$ const.

… frozen when $\omega < H$
(on superhorizon scales)

tensor (gravitational wave) modes also satisfy the same eq.

Starobinsky '79

generic predictions of inflation

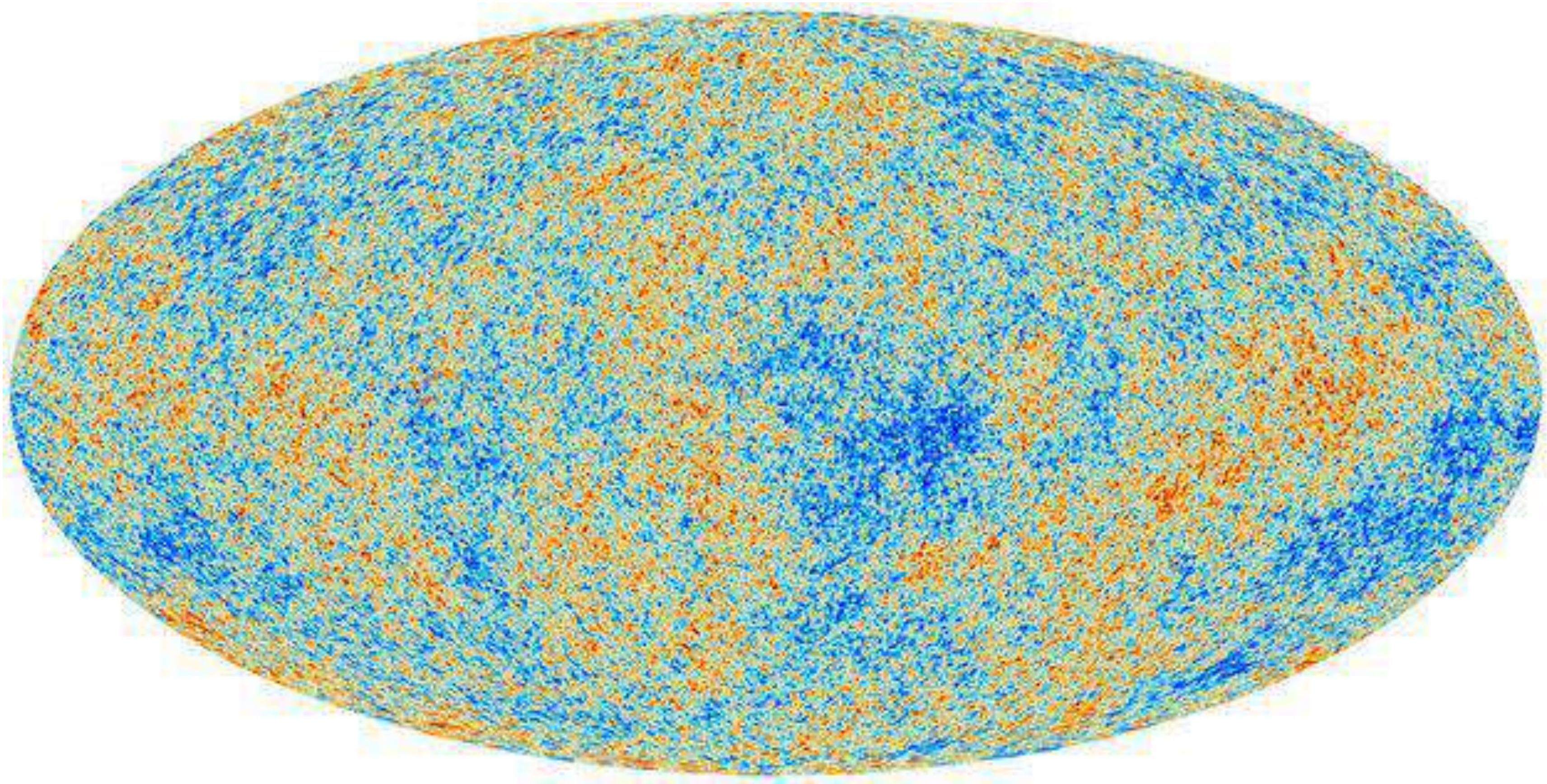
single-field slow-roll

- Spatially flat universe
- Almost scale invariant, adiabatic, Gaussian primordial scalar (curvature) perturbations
- Almost scale invariant, Gaussian primordial tensor (gravitational wave) perturbations

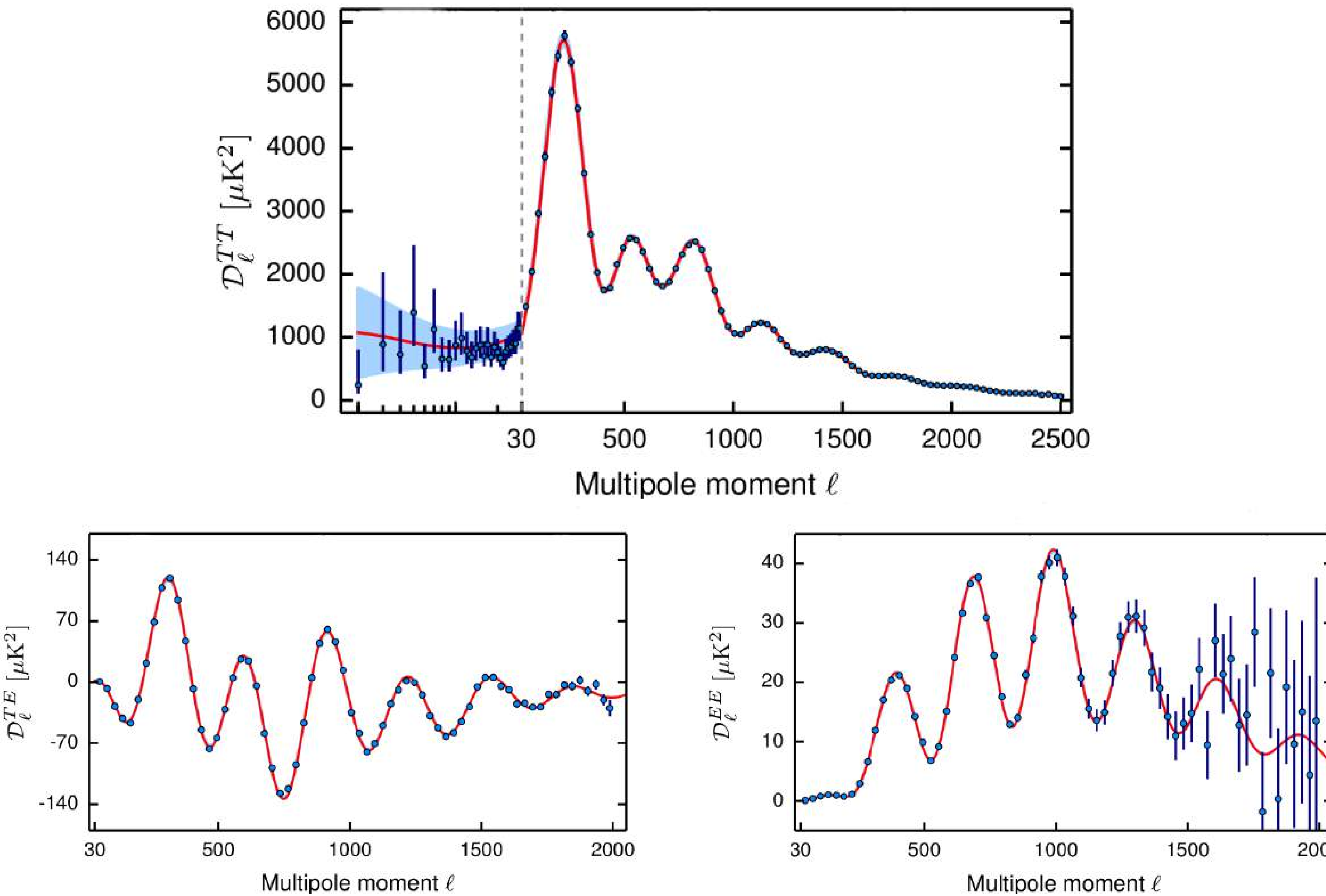
⇒ Generates CMB anisotropy
Origin of galaxies, stars, …

Observational results

CMB Full Sky Map by PLANCK

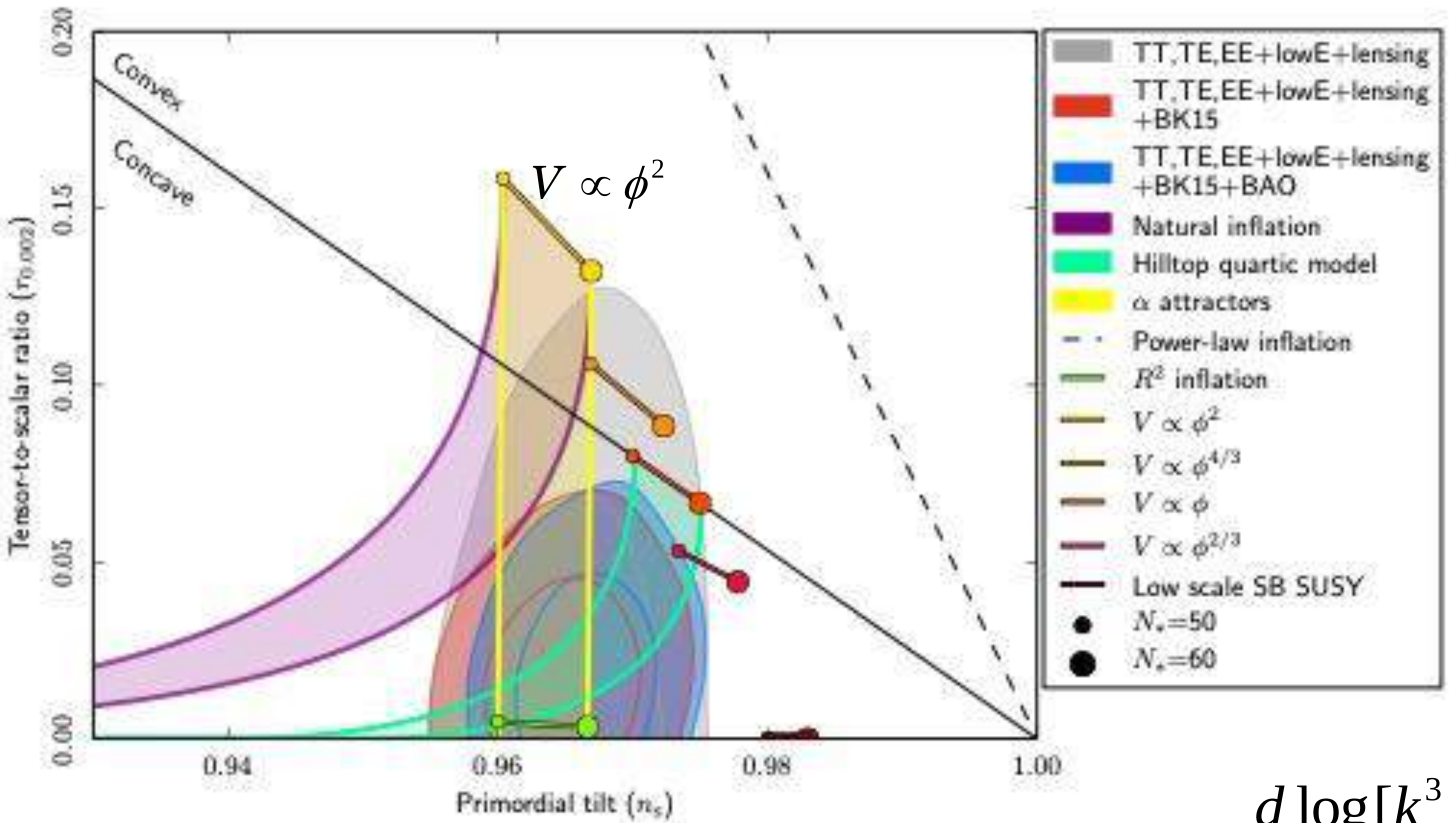


Planck TT, TE & EE spectrum



Planck constraints on inflation

Planck 2018 results X



- scalar spectral index: $n_s \sim 0.965$
- tensor-to-scalar ratio: $r < 0.03$
- simplest $V \propto \phi^2$ model is excluded

$$n_s - 1 \equiv \frac{d \log[k^3 P_S(k)]}{d \log k}$$

$$r \equiv \frac{P_T(k)}{P_S(k)}$$

The most important message is:

Inflation as the Origin of
All Structures
in the Universe

Current status

- scalar spectral index: $n_s<1$ at ~ 8 σ
- tensor/scalar ratio: $r < 0.03$ implies $E_{inflation} < 10^{16}$ GeV
- simple, canonical models are almost excluded (m$^2\phi^2$ model excluded at > 3 σ)
- R^2 (Starobinsky) model seems to fit best. But why? (large R^2 correction but negligible higher order terms)
- f_{NL}^{local} <O(1) suggests (effectively) single-field slow-roll (but non-slow-roll models with f_{NL}^{local} =O(1) not excluded)

elements of non-canonicality seem necessary

Beyond
(standard model of)
Inflation

non-canonical models

- Non-canonical kinetic term? (c_s <1?)

$$P_S \propto \frac{1}{c_s} \quad (c_s\text{: sound speed})\ ,\ f_{\rm NL}^{equil} \propto \frac{1}{c_s^2}$$

Planck: $c_s > 0.024$ at 95% CL

- non-minimal coupling to gravity? Higgs inflation?

$$V(\phi) + \xi \phi^2 R \quad \Rightarrow \quad r = \frac{P_T(k)}{P_S(k)} \propto \frac{1}{\xi}$$

Planck: $\xi > O(10)$?

- scalar-tensor with derivative couplings? Horndeski?

$$c_s < 1,\ \ c_{s,T} < 1,\ c_s \neq c_{s,T}$$

↑ tensor propagation speed

non-existence of Einstein frame?

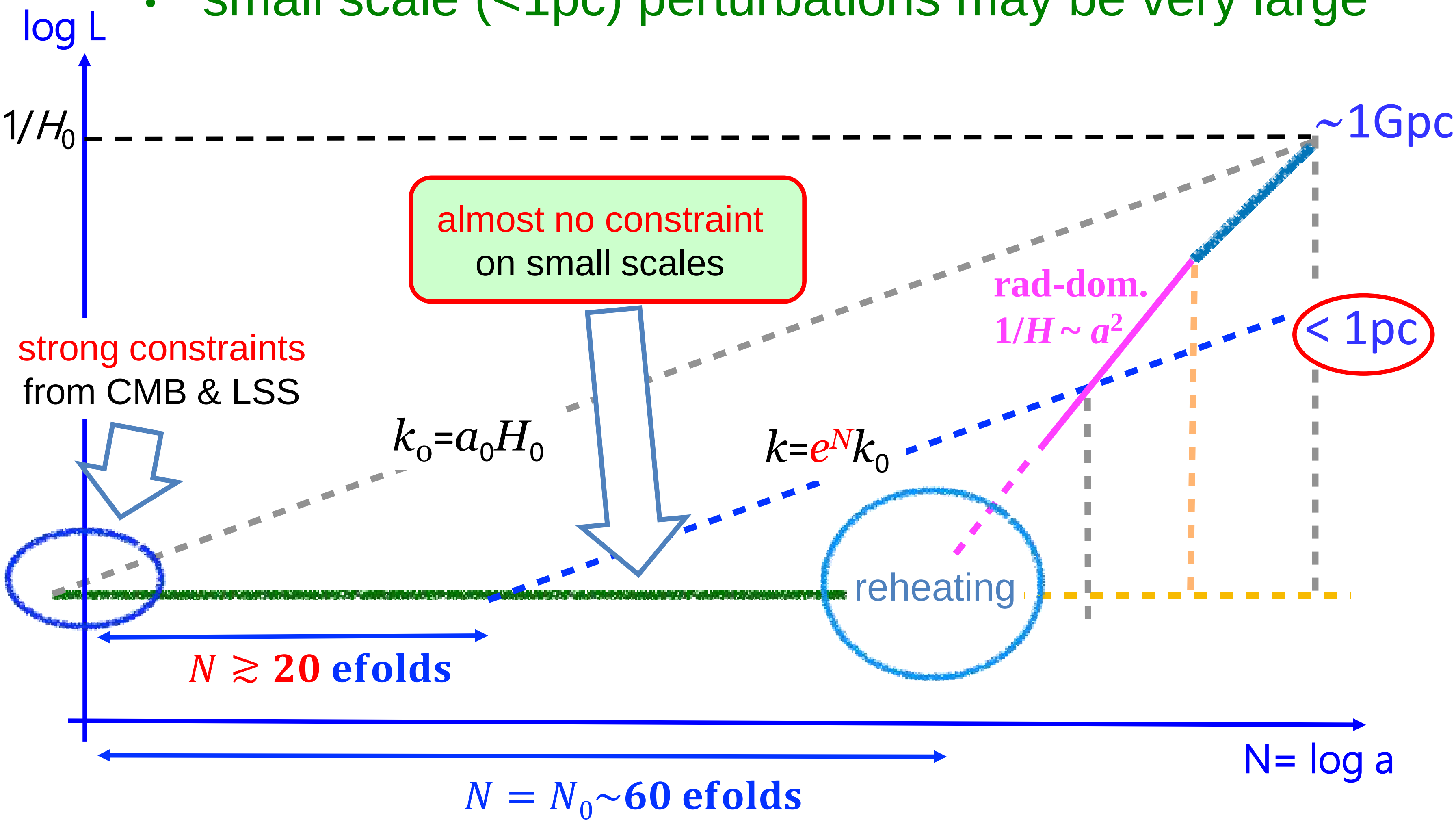
↕ definition of inflation?

- multi-field models, non-attractor inflation, …

↕ features in the potential due to other dofs?

New physics on small scales?

- we have no clues about the late stage of inflation
- small scale (<1pc) perturbations may be very large

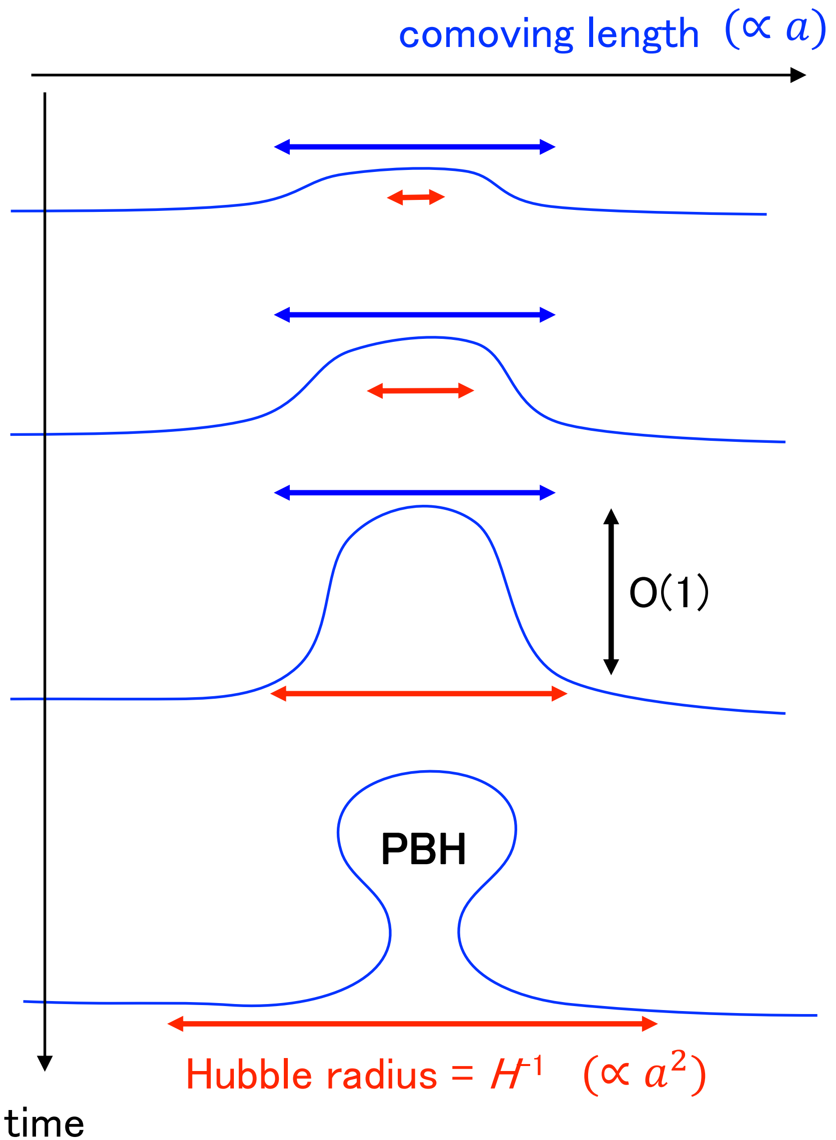


Primordial Black Holes!

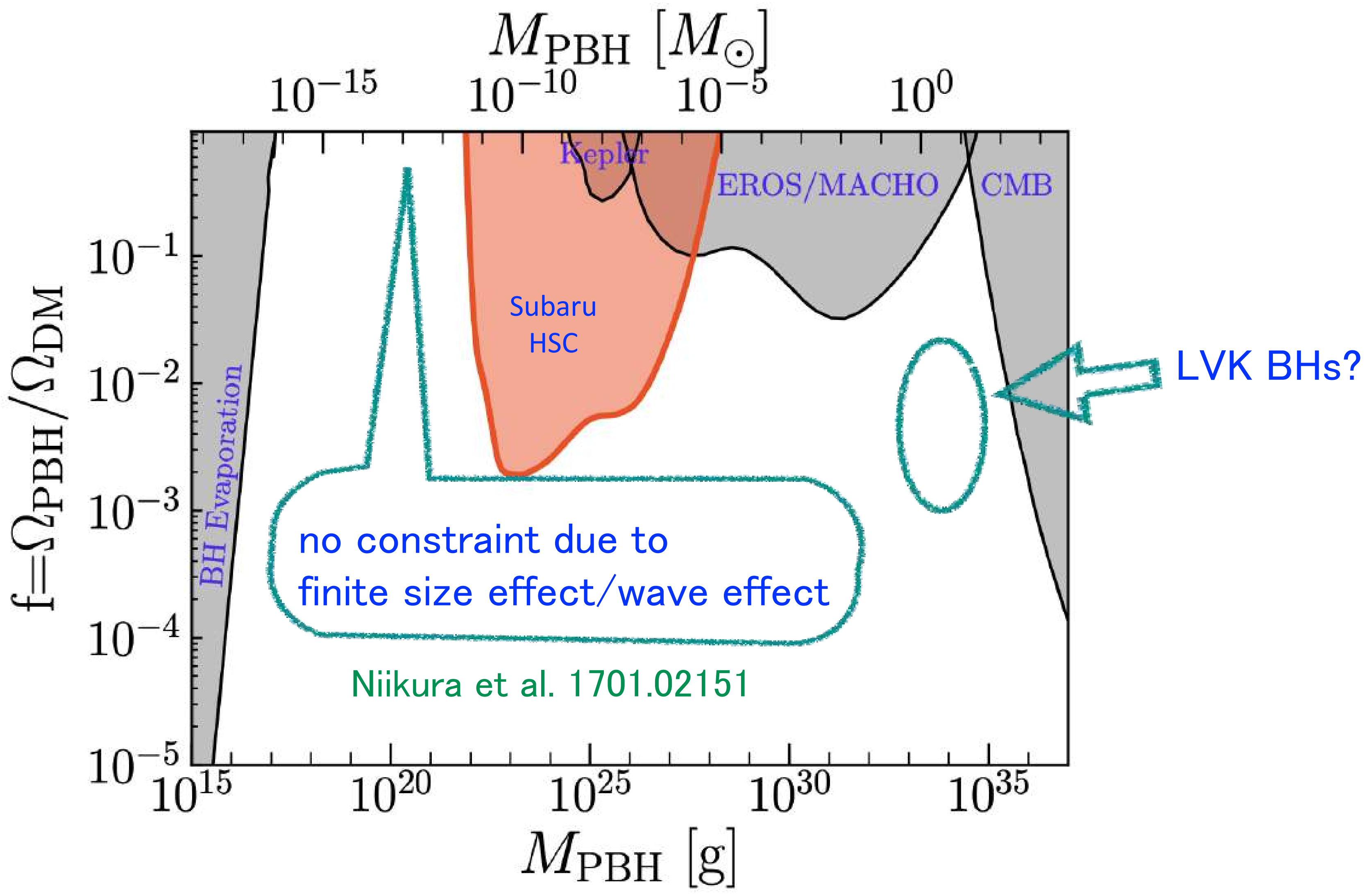
- Primordial Black Holes (PBHs) are those formed in the very early universe, conventionally when the universe was radiation-dominated.
- Presumably they originate from a large positive curvature perturbation produced during inflation (which hence should be a rare event).
- For a BH to form during radiation dominance, the perturbation must be O(1) on the Hubble horizon scale.

$$\boldsymbol{M_{\mathrm{PBH}} \sim M_{\mathrm{horizon}}}$$

$$\sim \left(\frac{100\mathrm{MeV}}{T}\right)^2 M_\odot \sim \left(\frac{\ell}{1\mathrm{pc}}\right)^2 M_\odot$$

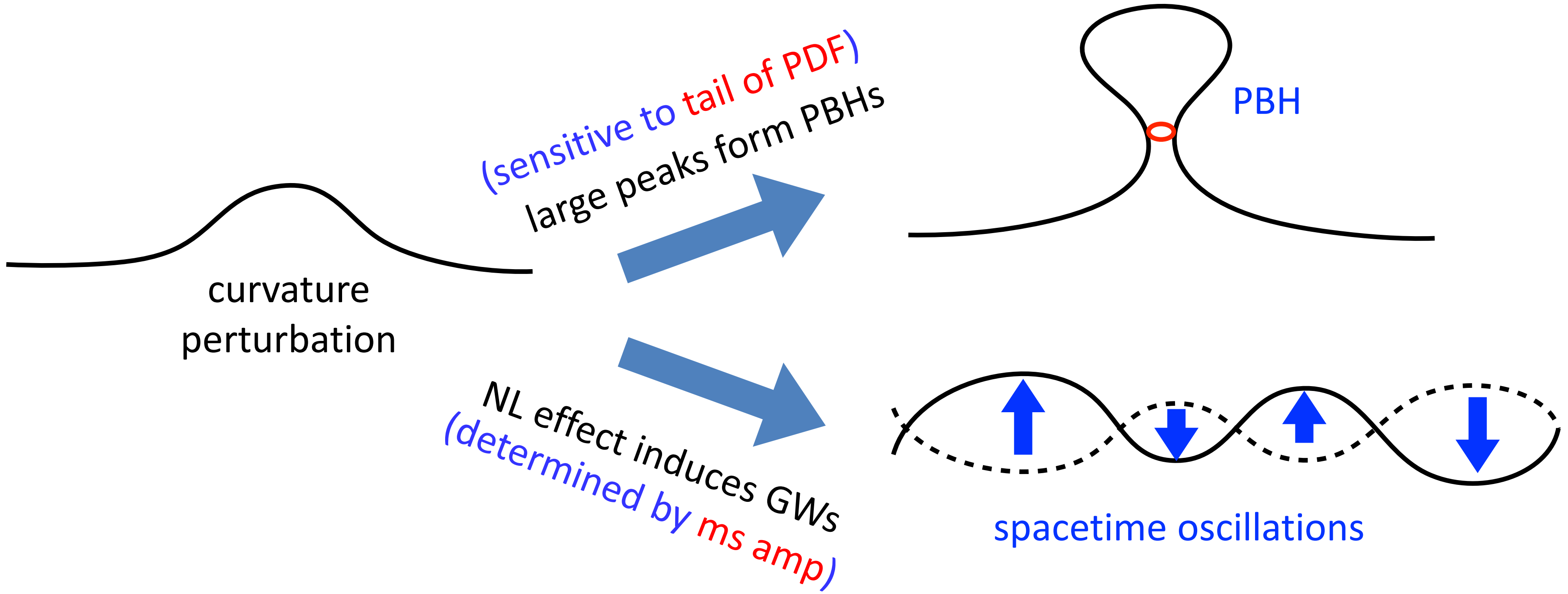


observational constraints



big window at $M_{\rm PBH} \approx 10^{17} - 10^{22}$g ⟺ $T_{\rm re\text{-}entry} \sim 10^4$ -10^8 GeV

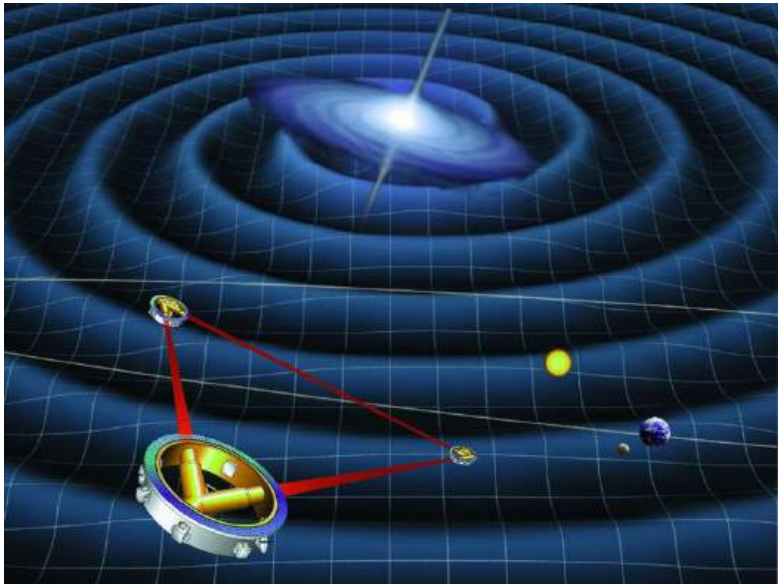
GWs can capture PBHs!



PBHs = CDM with $M_{PBH} \sim 10^{21}$g generates GWs with f~10^{-3} Hz ⇨ Background GWs at LISA band

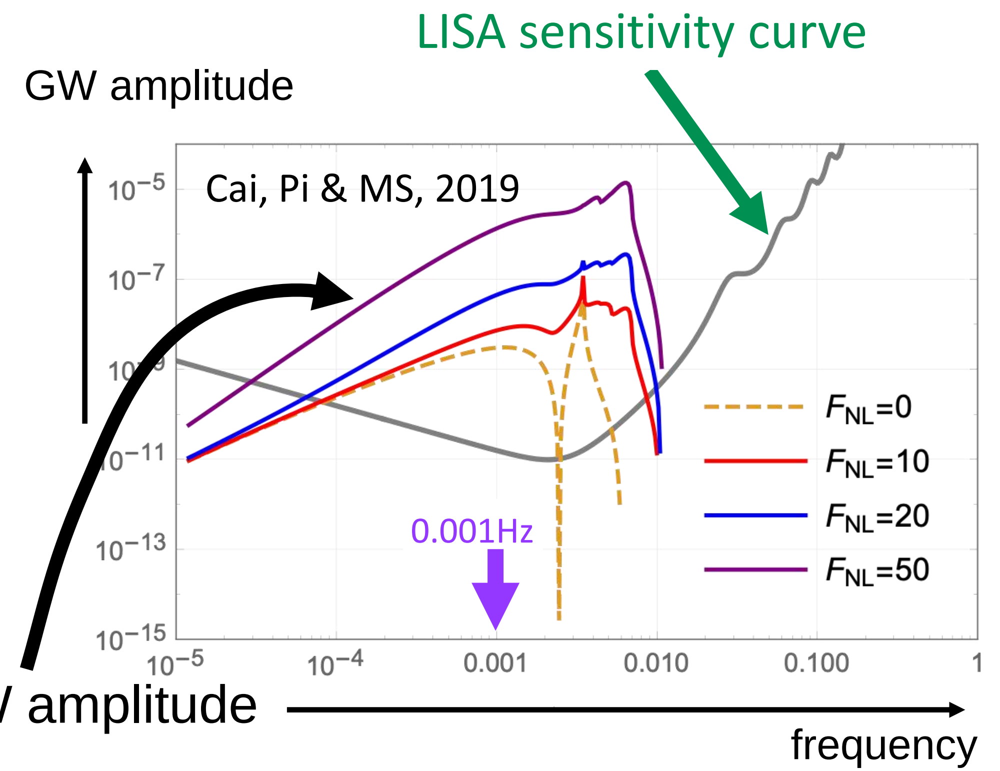
PBHs =LV BHs with $M_{PBH} \sim 10 M_\odot$ generates GWs with f~10^{-8} Hz ⇨ Background GWs at PTA band

GW observatories in space



LISA 2035? (ESA+NASA)
arm length: 5,000,000 km

Taiji 203X ? (China)
arm length: 3,000,000 km

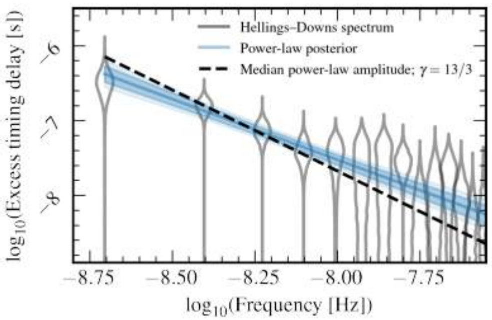


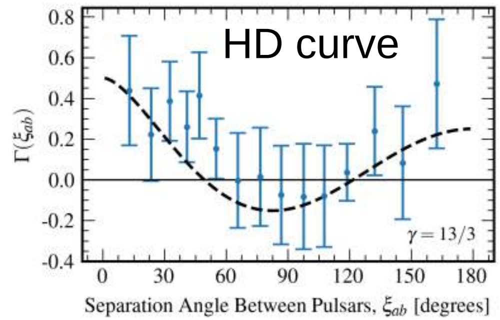
LISA/Taiji will prove/disprove PBH=CDM scenario

Recent News from NANOGrav + CPTA + EPTA

Evidence for Stochastic GW Background!?

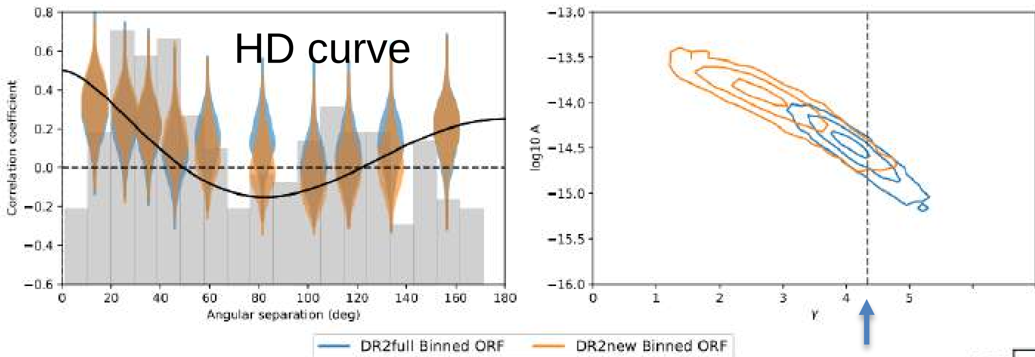
NANOGrav: 2306.16213, EPTA: 2306.16214, CPTA: 2306.16216





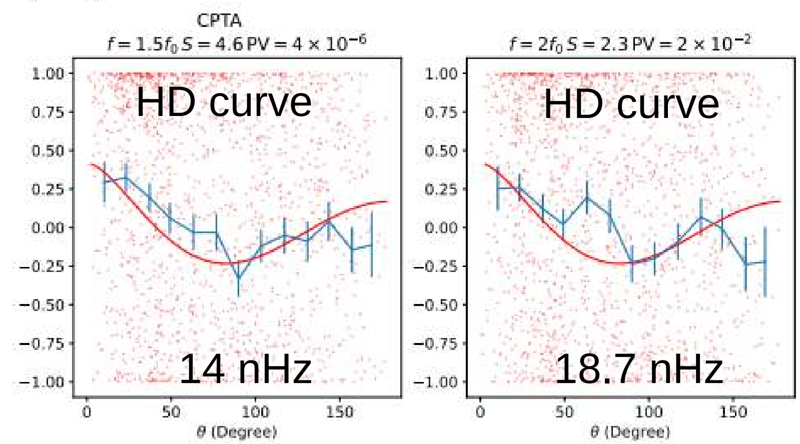
NANOGrav 15 yr data

γ=13/3: expected index if SMBH mergers



EPTA 25 yr/10 yr new data

γ=13/3



CPTA 3 yr data

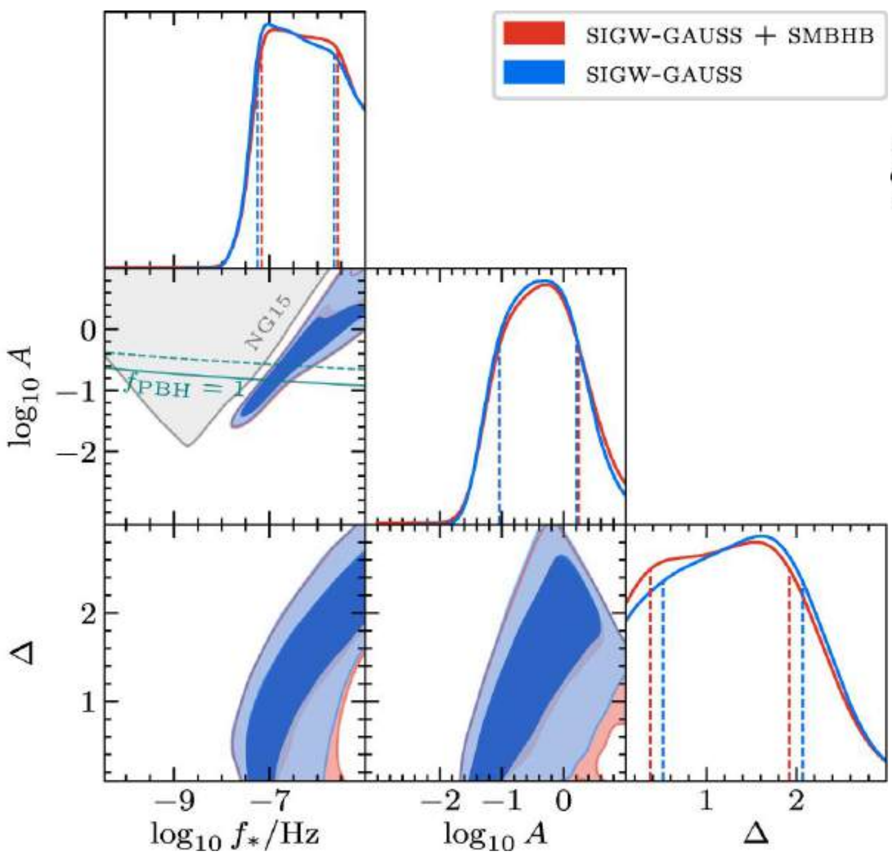
frequency dependence

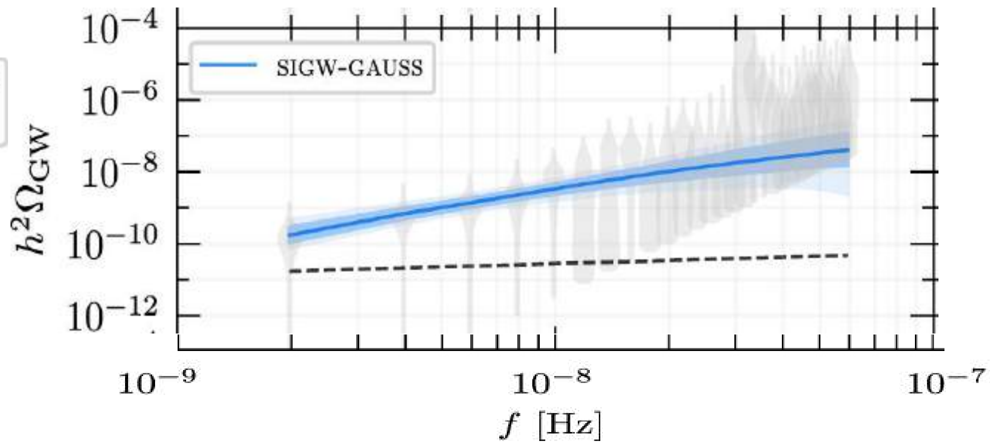
induced GWs?

2306.16219

If NANOGrav Data = iGWs, with

$$\mathcal{P}_R(k) = \frac{A}{\sqrt{2\pi}\,\Delta} \exp\left[-\frac{1}{2}\left(\frac{\ln k - \ln k_*}{\Delta} \right)^2 \right]$$





$A \sim 10^{-0.4\pm0.6}$

$\Delta \sim 1.6^{+0.4}_{-1.0}$

$f_* \sim 10^{-7}\,{\rm Hz}$

$\Leftrightarrow M_{\rm PBH} \sim 0.1 M_\odot$

if

$$\frac{A}{\sqrt{2\pi}\Delta} \sim 0.1$$

too large!?

Future issues

- initial condition for inflation, multiverse?
- successful reheating?
- non-linear effects, non-Gaussianities?
- PBHs, induced GWs?
- Other GW signatures?
- modified gravity?
- ……

Identification of Inflaton!

Inflation as the base for exploring
Physics of the Early Universe

Entering an era of

Observational/Experimental
Inflationary Cosmology!

Happy 60th Birthday, Hitoshi!