Inflationary Universe:
Known Knowns,
Known Unknowns,
and Unknown Unknowns

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Introduction

What is Inflation?

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

- Inflation is a quasi-exponential expansion of the Universe at its very early stage; perhaps at $t \sim 10^{-35}$ sec.

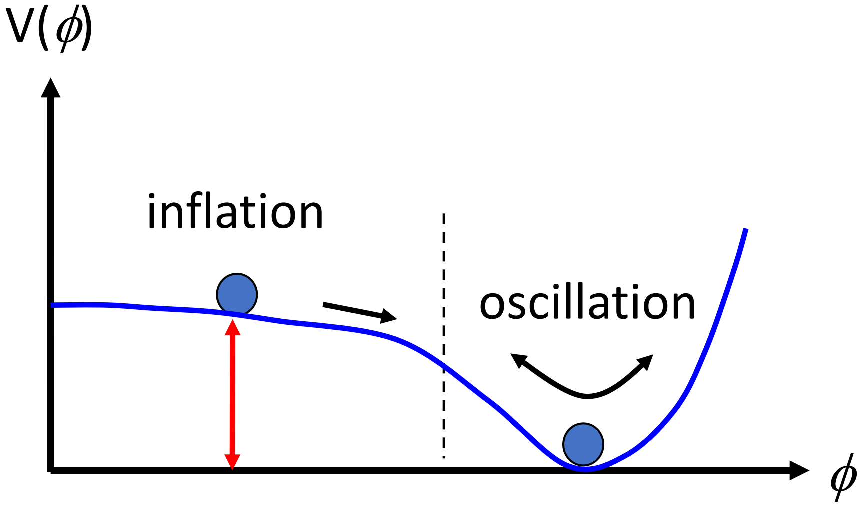
- It was meant to solve the initial condition (singularity, horizon & flatness, etc.) problems in Big-Bang Cosmology:
  - if any of them can be said to be solved depends on precise definitions of the problems.

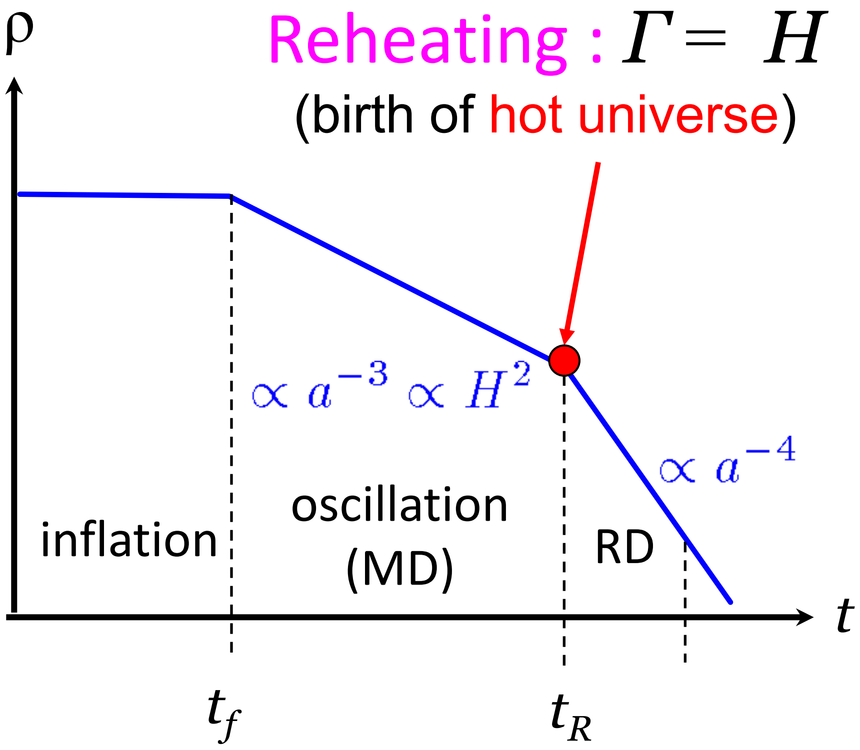
- Quantum vacuum fluctuations during inflation turn out to play the most important role. They give the initial condition for all the structures in the Universe.

- Cosmic gravitational wave background is also generated.

From inflation to bigbang

After inflation, vacuum energy is converted to thermal energy (called "re"heating) and hot Bigbang Universe is realized.





more on the meaning of inflation

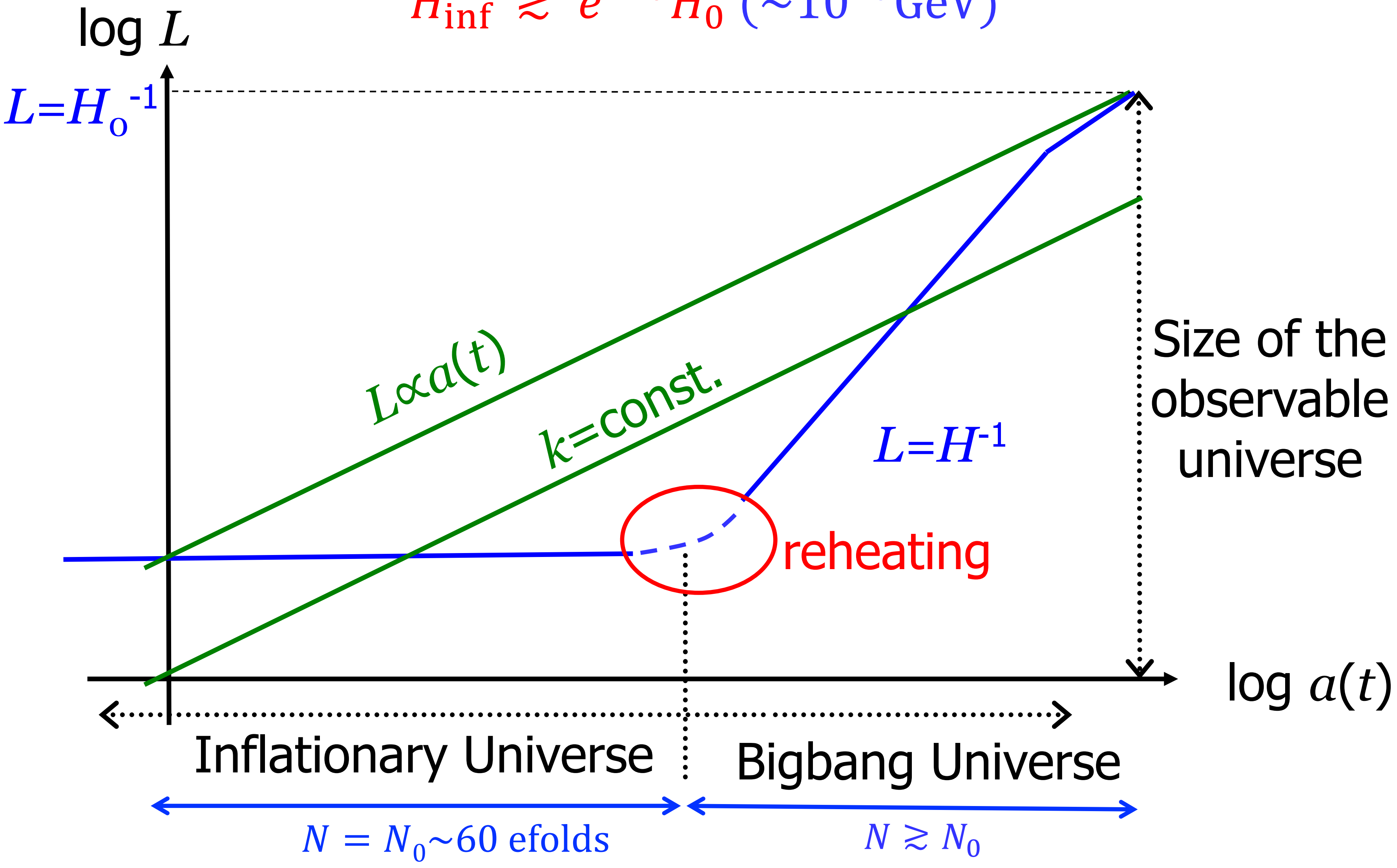
1. Homogeneity and isotropy are the (most important) assumptions, NOT a consequence of inflation.
2. Quasi-exponential expansion in the "Einstein frame": conformal invariant definition.
3. At least 50-60 e-folds before the end of inflation: solving "horizon problem"
4. Don't care what happened before inflation: predictions are almost independent of initial conditions.

1 & 2: basic assumptions/definition of inflation

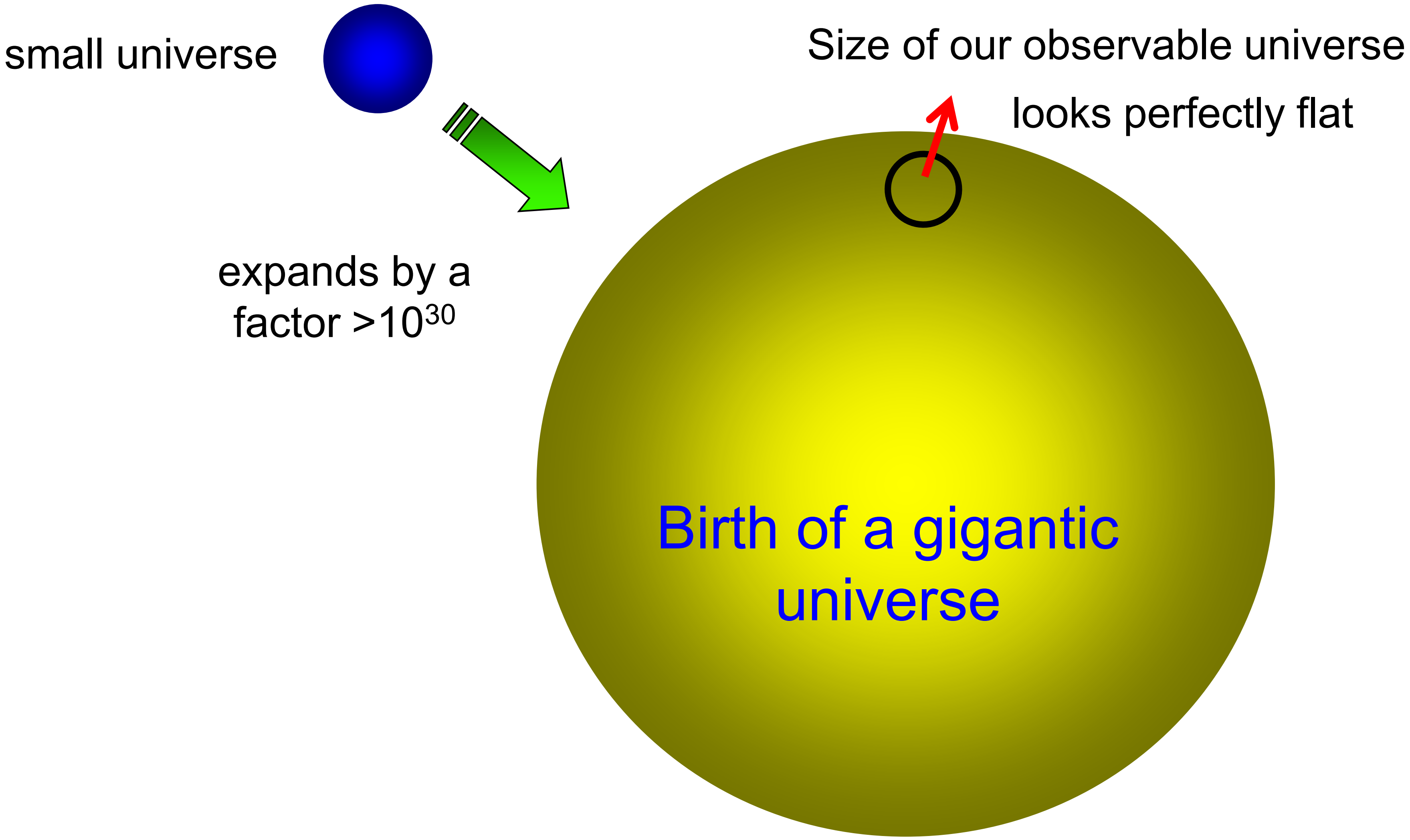
Kinematics

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

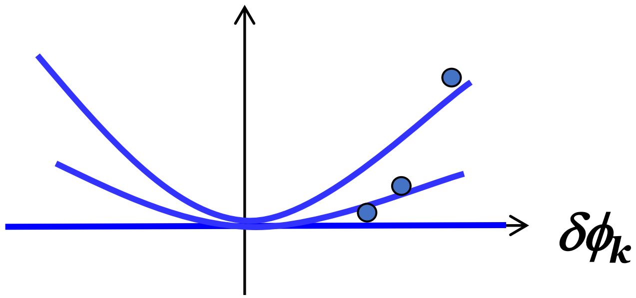
Seed of cosmological perturbations

Mukhanov & Chibisov '81, ….

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

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

harmonic oscillator with friction term and time-dependent ω



$\delta\phi_k \rightarrow$ const.

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

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

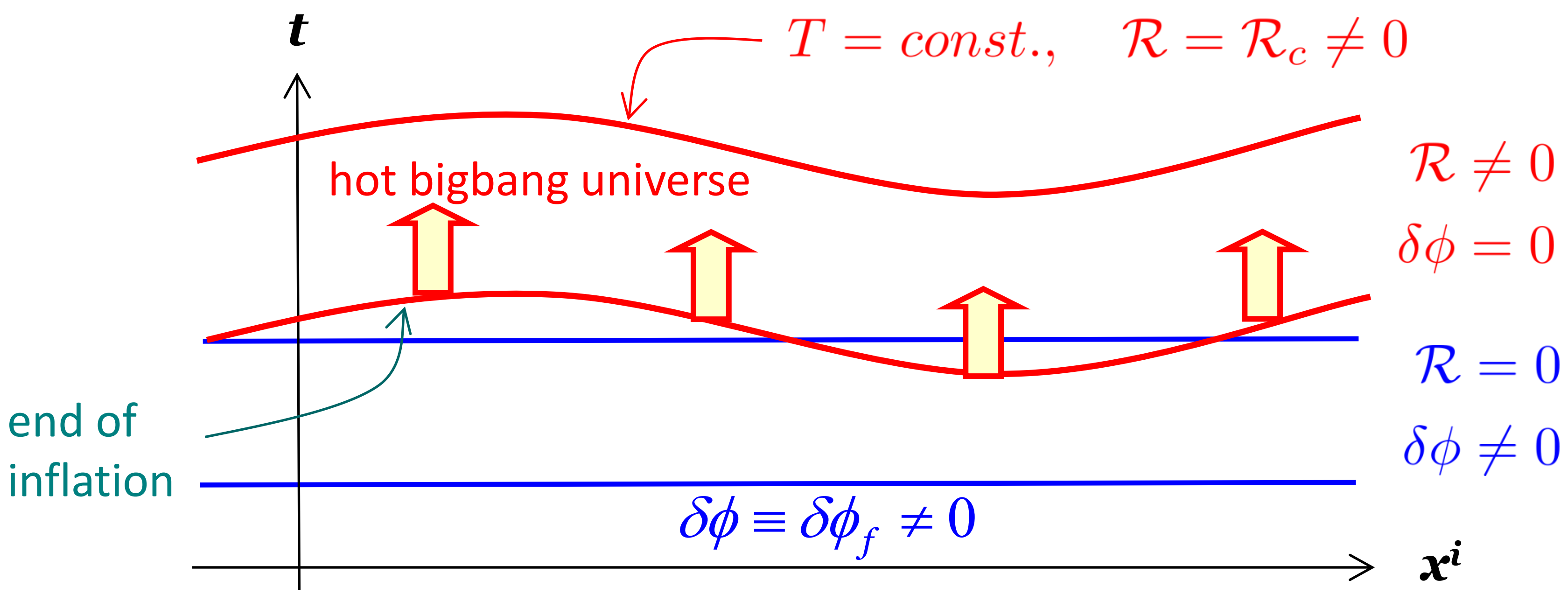
Starobinsky '79

Generation of Curvature Perturbation

curvature (potential) perturbation $\mathcal{R}$: $\delta R^{(3)} = -\frac{4}{a^2}\nabla^2\mathcal{R}$

curvature perturbation on comoving ($\delta\phi$ =0) slices $\mathcal{R}_c$ ~ Newton potential

- $\delta\phi$ is frozen on "flat" ($\mathcal{R}$ =0) 3-surface (t=const. hypersurface) $\mathcal{R}_c = -\frac{H}{\dot{\phi}}\delta\phi_f$
- Inflation ends/damped osc starts "comoving" (ϕ =const.) on 3-surface.



generic predictions of inflation

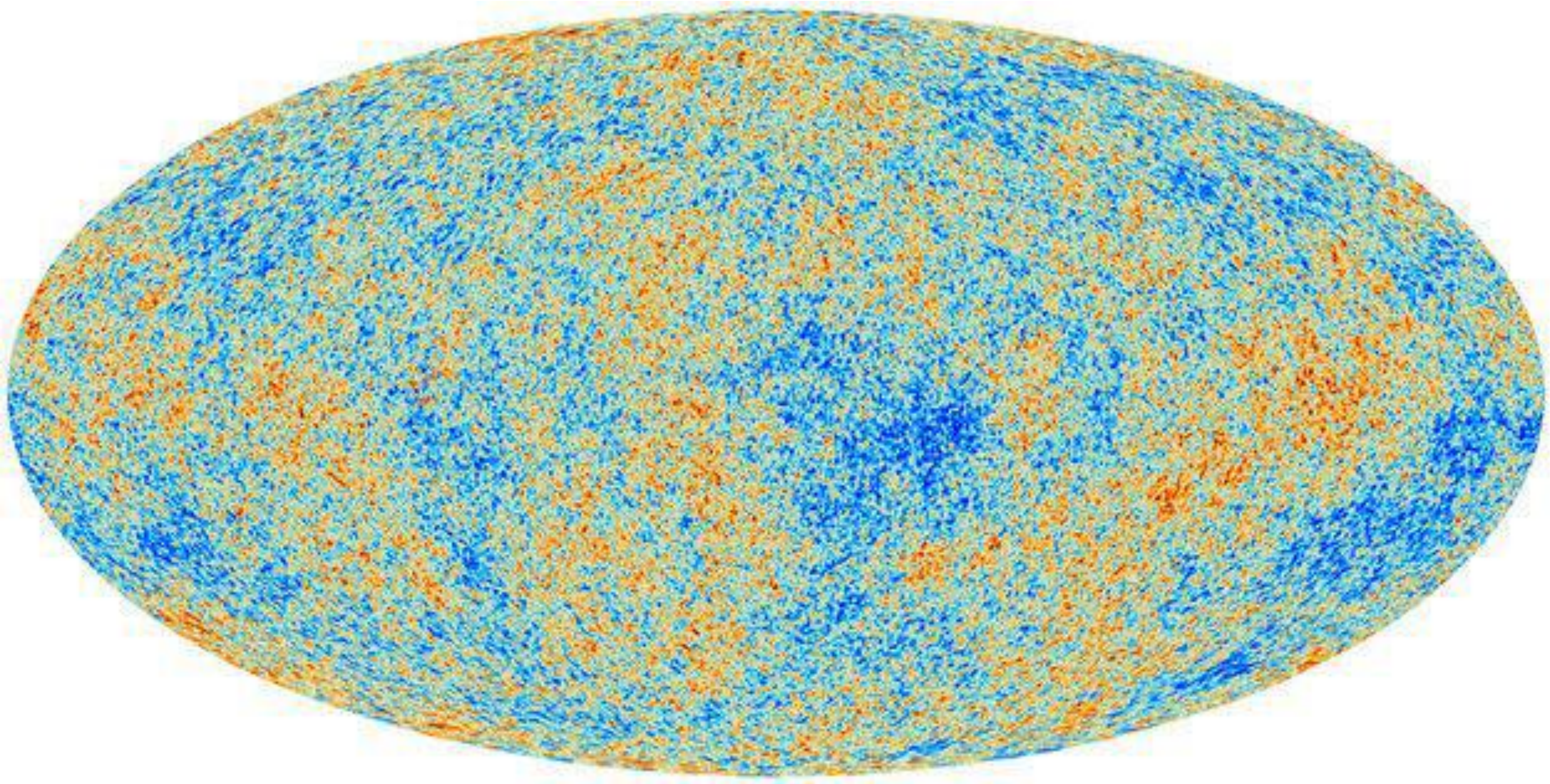
single-field slow-roll

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

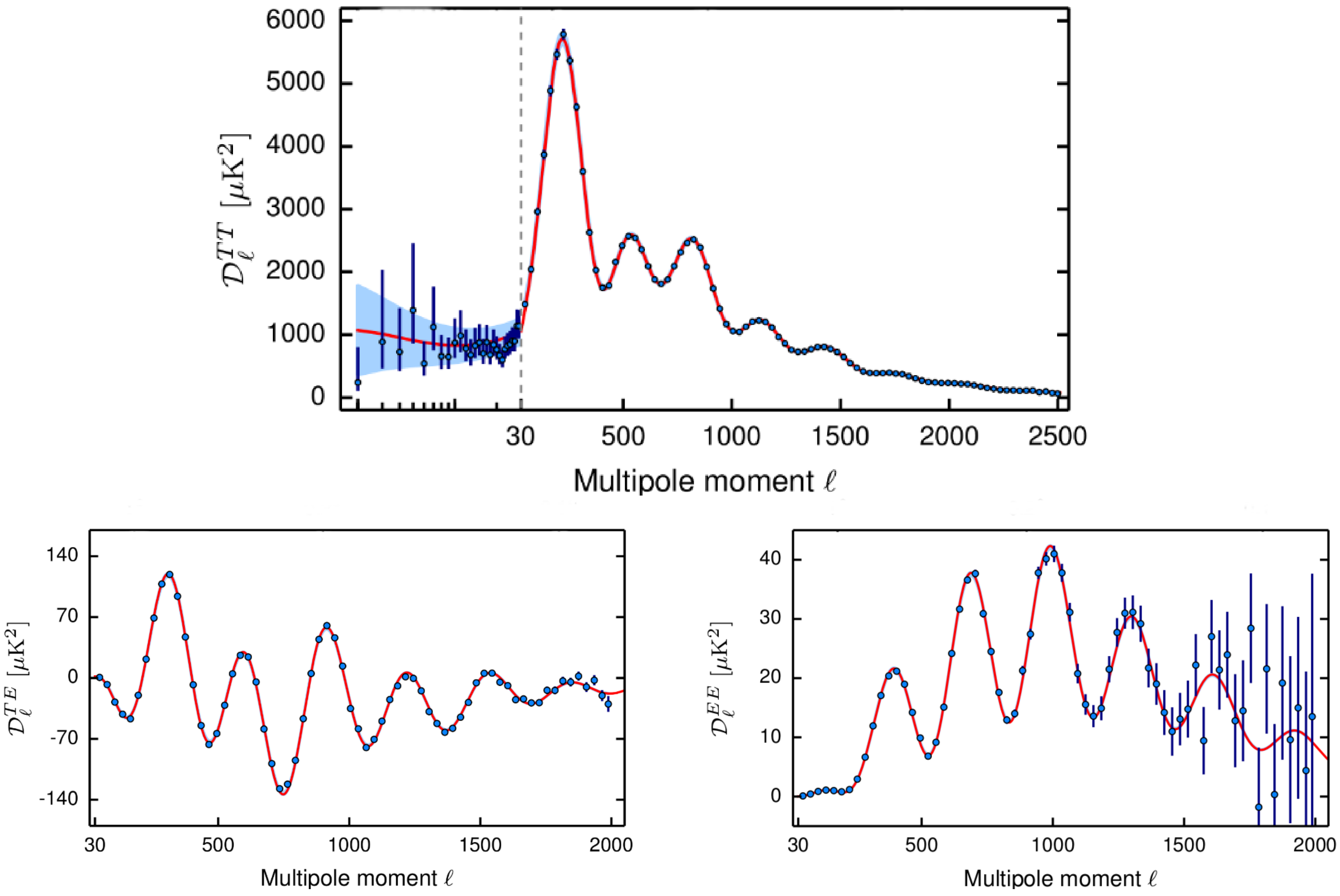
⇨ Generates CMB anisotropy
Origin of galaxies, stars, …

Observational results

CMB Full Sky Map by PLANCK



Planck TT, TE & EE spectrum



- Amplitude of curvature perturbation:

$$\mathcal{R}_c = \left.\frac{H^2}{2\pi\dot{\phi}}\right|_{k/a=H}$$

Mukhanov (1985), MS (1986)

$$\mathcal{R}_{c,\mathrm{obs}} \sim 10^{-5} \;\Rightarrow\; V^{\frac{1}{4}}(\phi) \sim 10^{16}\,\mathrm{GeV?}$$

- Power spectrum index:

$$M_P \equiv \frac{1}{\sqrt{8\pi G}} \sim 2.4\times 10^{18}\,\mathrm{GeV}: \text{Planck mass}$$

$$\frac{4\pi k^3}{(2\pi)^3} P_S(k) = \left[\frac{H^2}{2\pi\dot{\phi}}\right]^2_{k/a=H} = Ak^{n_S-1}\;;\quad n_S - 1 = M_P^2\left(2\frac{V''}{V} - 3\frac{V'^2}{V^2}\right)$$

Stewart-Lyth (1993)

$n_{S,\mathrm{Planck}} - 1 = -0.0355 \pm 0.0049 \;\Leftrightarrow\; n_S - 1 \sim -0.04$ for a typical model

- Tensor (gravitational wave) spectrum: Mukhanov & Chibisov (1981)

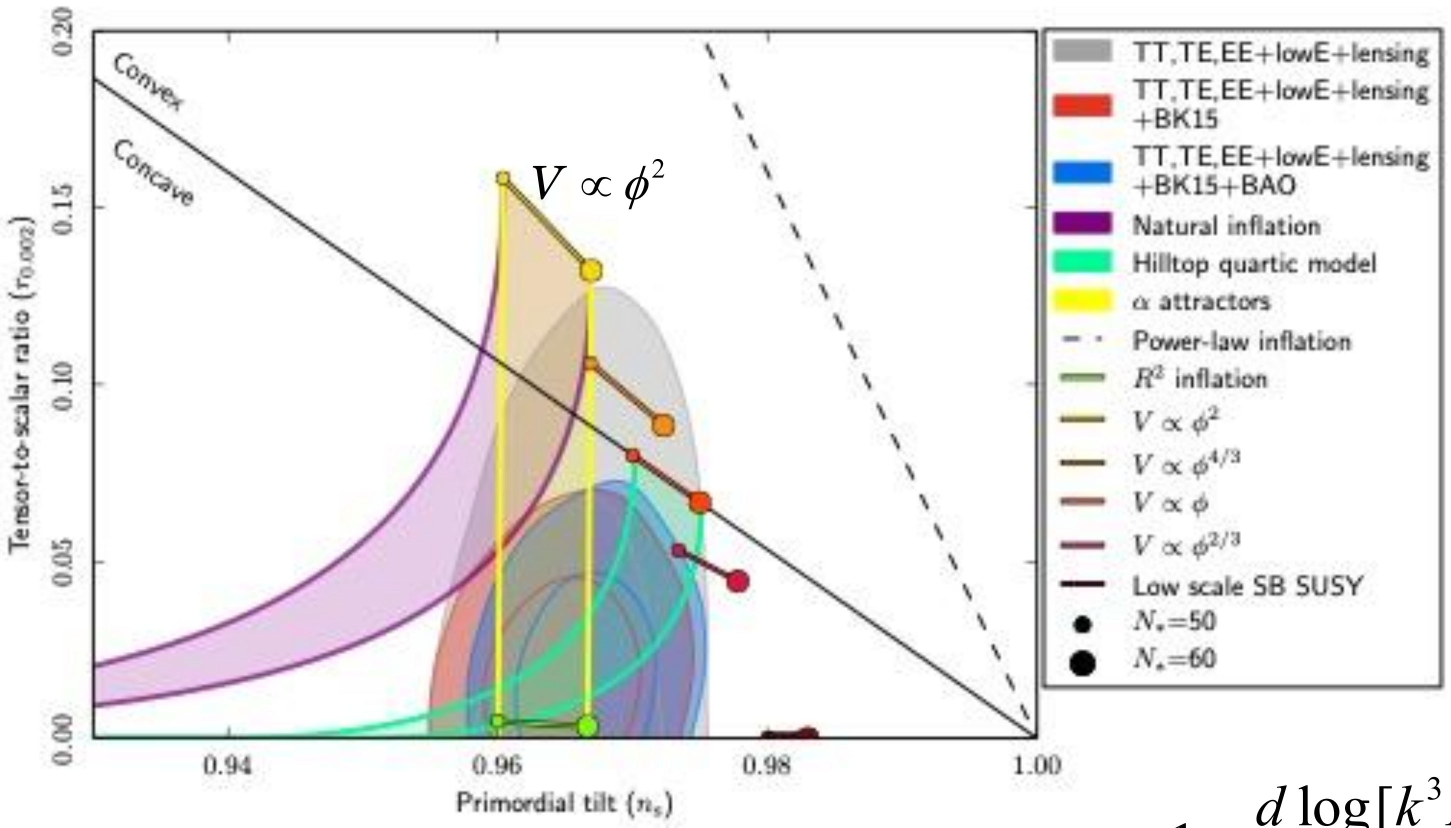
$$\frac{4\pi k^3}{(2\pi)^3} P_T(k) = Ak^{n_T}\;;\quad n_T = -\frac{1}{8}\frac{P_T(k)}{P_S(k)} \equiv -\frac{r}{8}$$

Liddle-Lyth (1992)

to be observed by LiteBIRD !

Planck constraints on inflation

Planck 2018 results X



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

- scalar spectral index: n_s ~ 0.965 (0.974?)
- tensor-to-scalar ratio: r < 0.03
- simplest $V \propto \phi^2$ model is excluded

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

Implications

The most important message is:

Inflation as the Origin of
All Structures
in the Universe

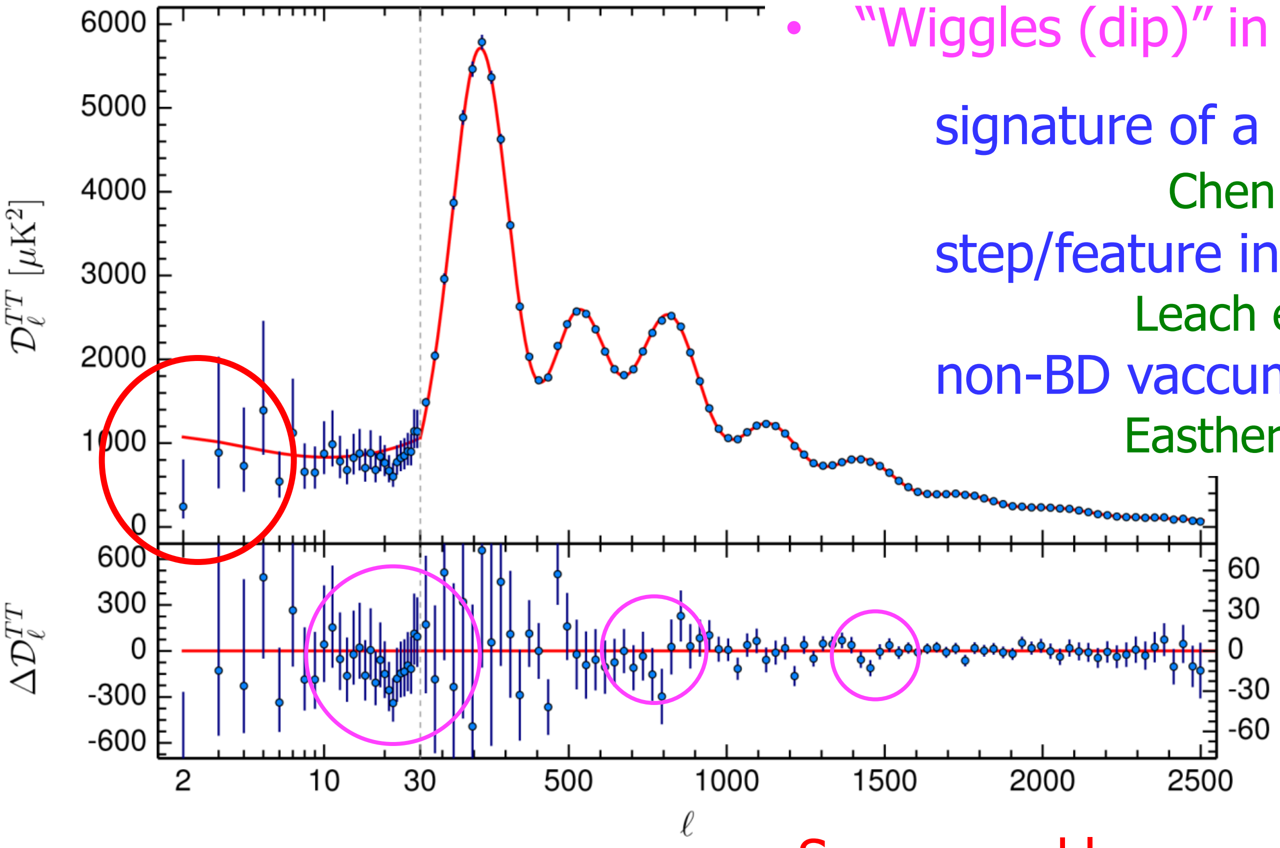
Current status

- 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

Anomalies on (very) large scales?



- "Wiggles (dip)" in the power spectrum

  signature of a heavy field?

  Chen '11, …

  step/feature in potential?

  Leach et al. '01, ….

  non-BD vaccum?

  Easther et al. '02,….

- Suppressed large scale fluctuations

  quantum tunneling, open inflation?

  Linde, MS & Tanaka '99, ….

Cosmic landscape?

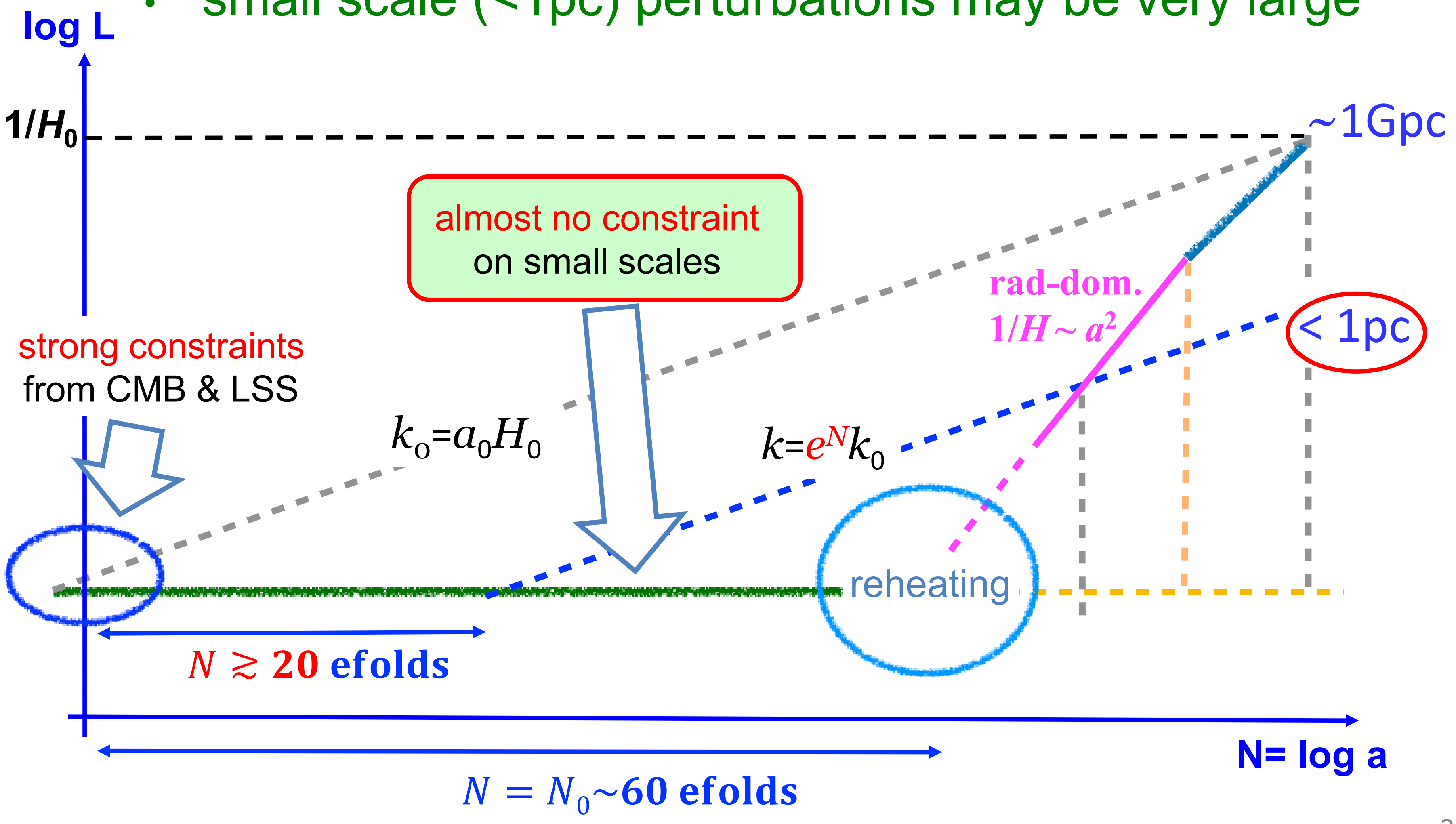
string theory suggests an intriguing picture of the early universe

Maybe we live in one of these vacua…

anomalies might be signatures of multiverse

New physics on small scales?

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

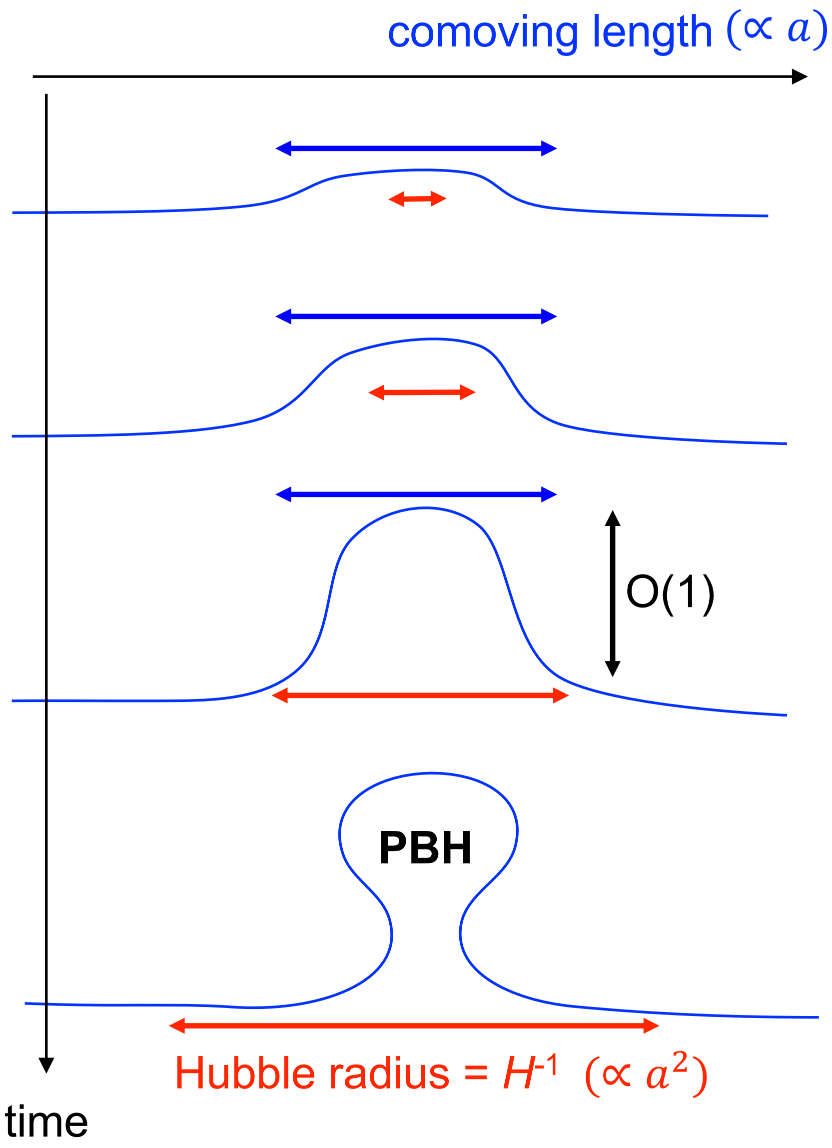


Primordial Black Holes!

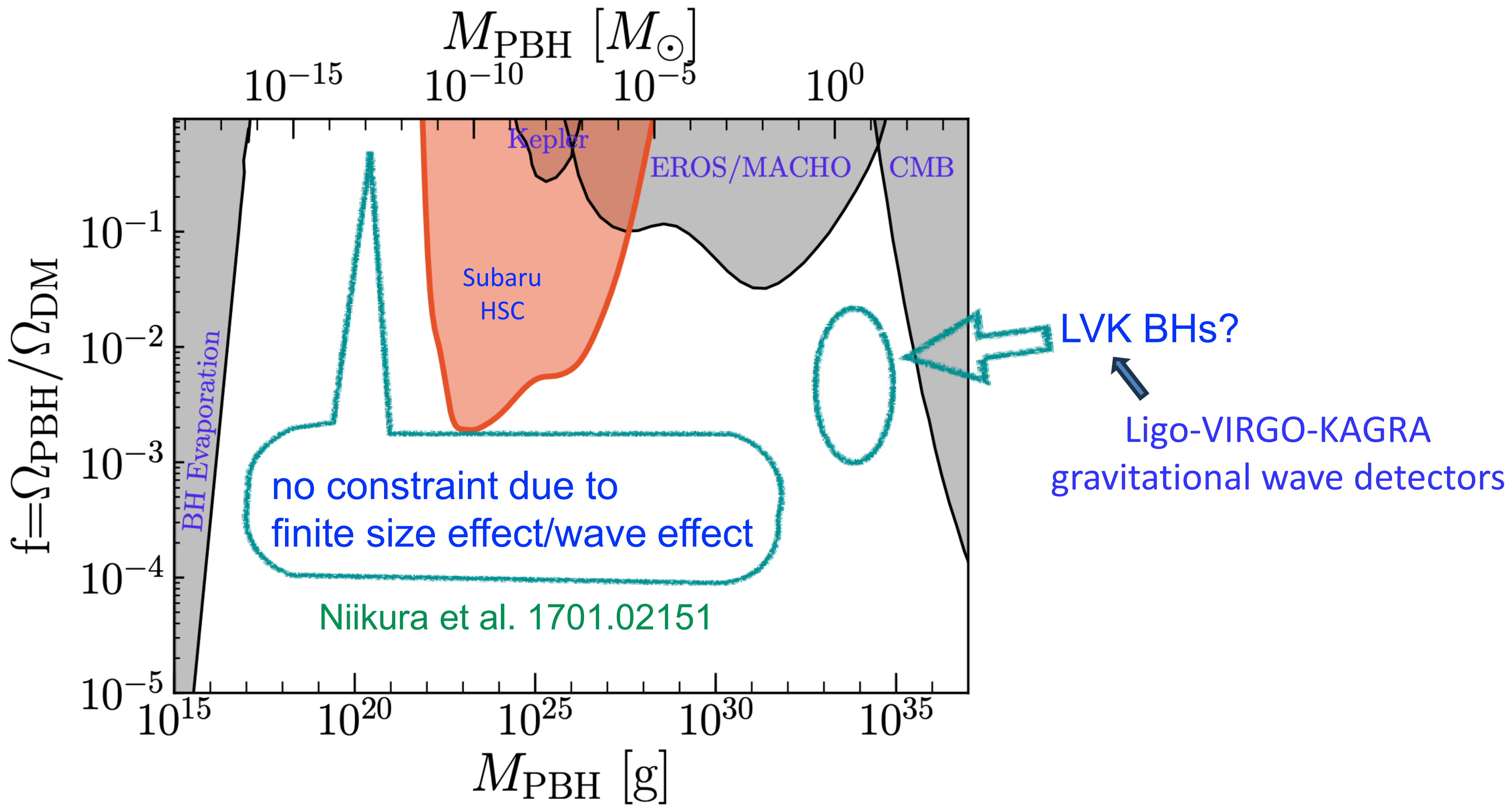
- Primordial Black Holes (PBHs) are those formed in the very early universe, conventionally when the universe was radiation-dominated.
- Presumably they originate from a large positive curvature perturbation produced during inflation (which hence should be a rare event).
- For a BH to form during radiation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

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

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

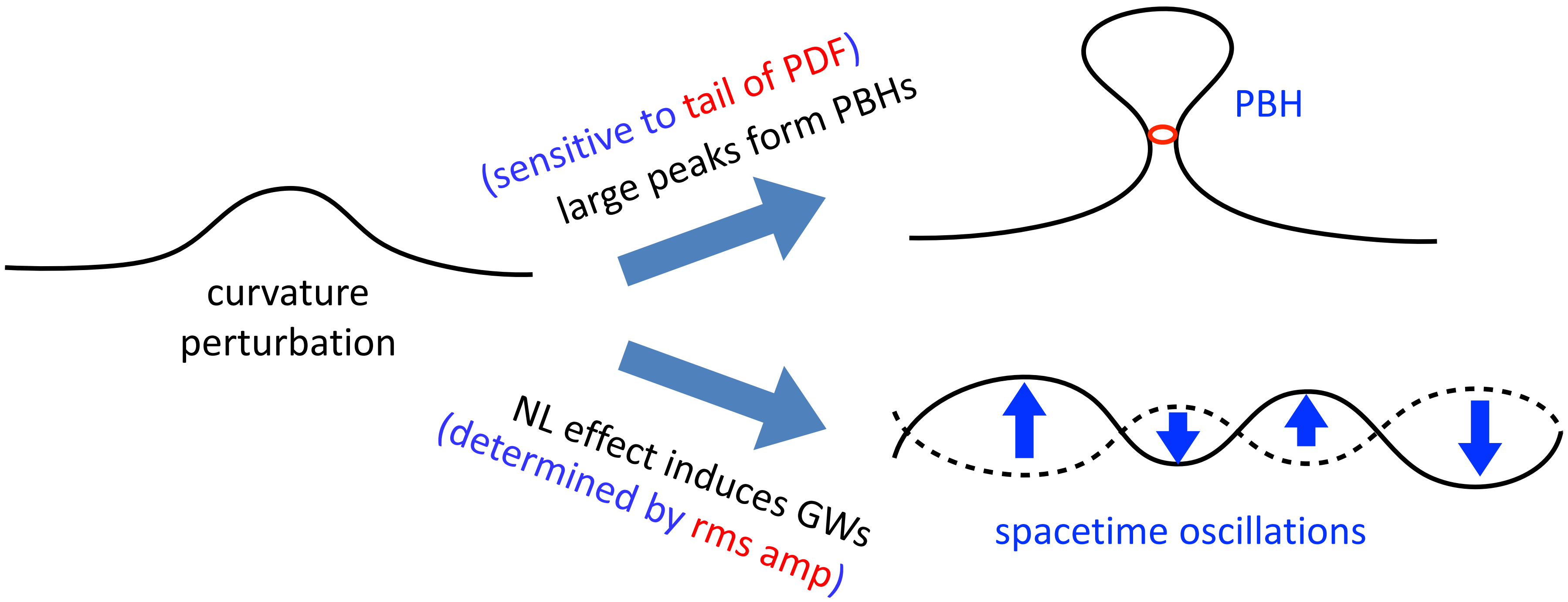


observational constraints



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!



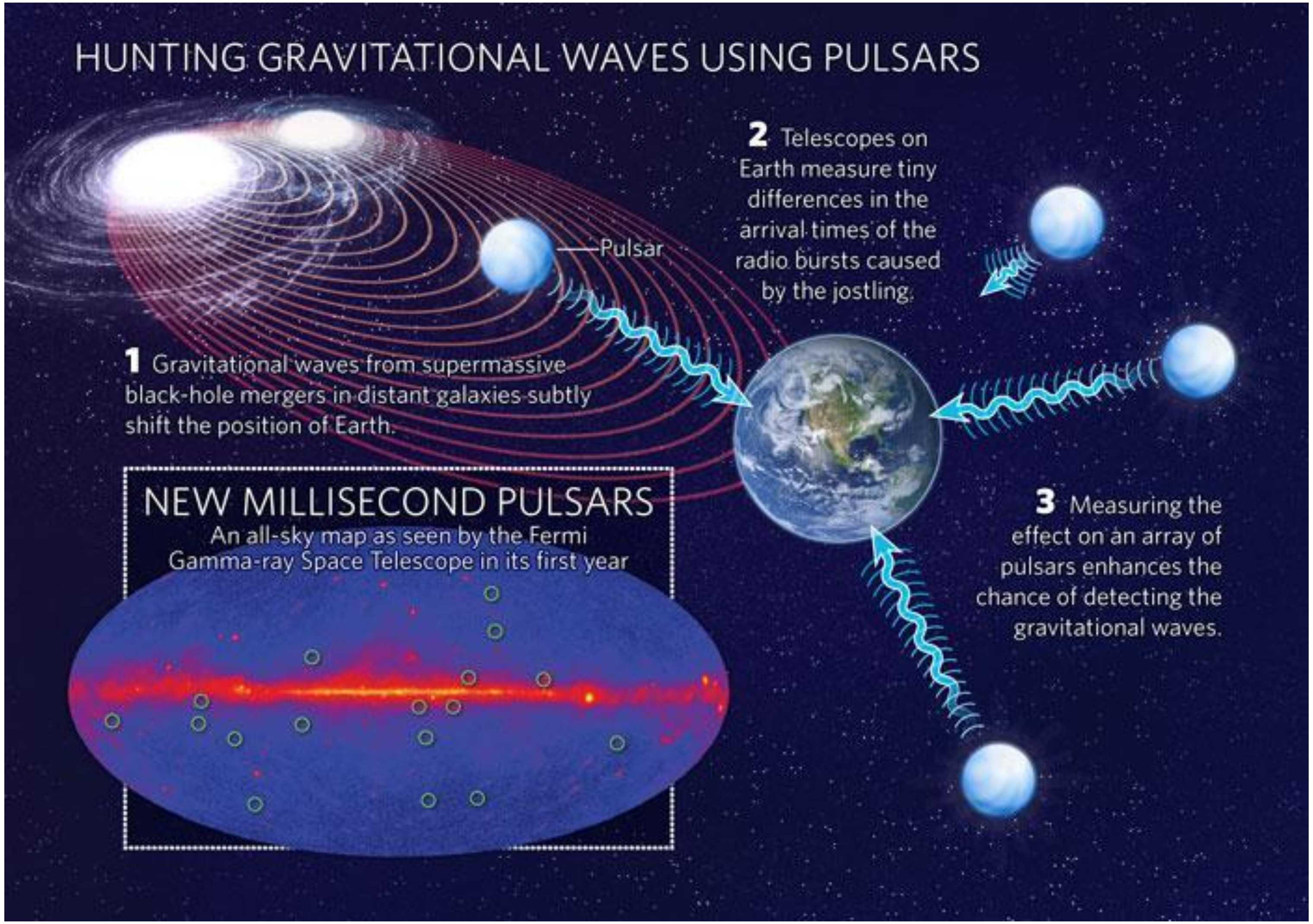
PBHs = CDM with $M_{PBH} \sim 10^{21}$g
generates GWs with f~10^{-3} Hz

⇨ Background GWs
at LISA band

PBHs =LVK BHs with $M_{PBH} \sim 10 M_{\odot}$
generates GWs with f~10^{-8} Hz

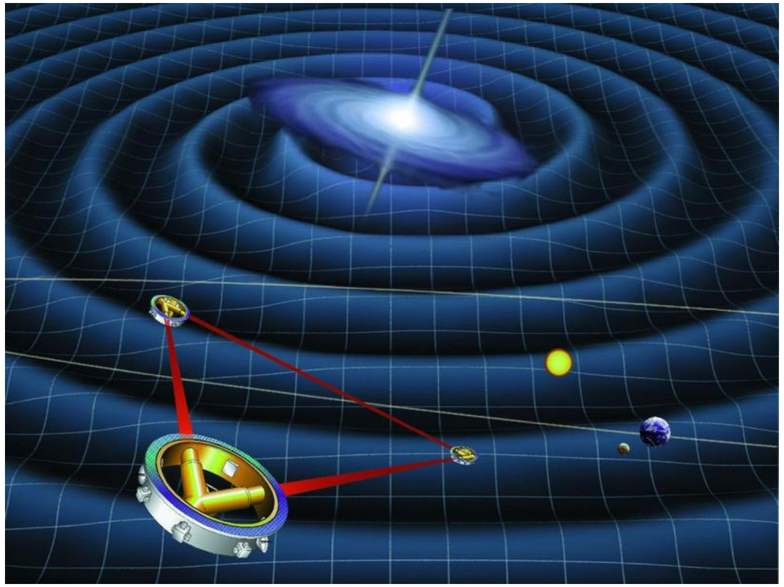
⇨ Background GWs
at PTA band
(Pulsar Timing Array)

PTAs can detect Gravitational Waves



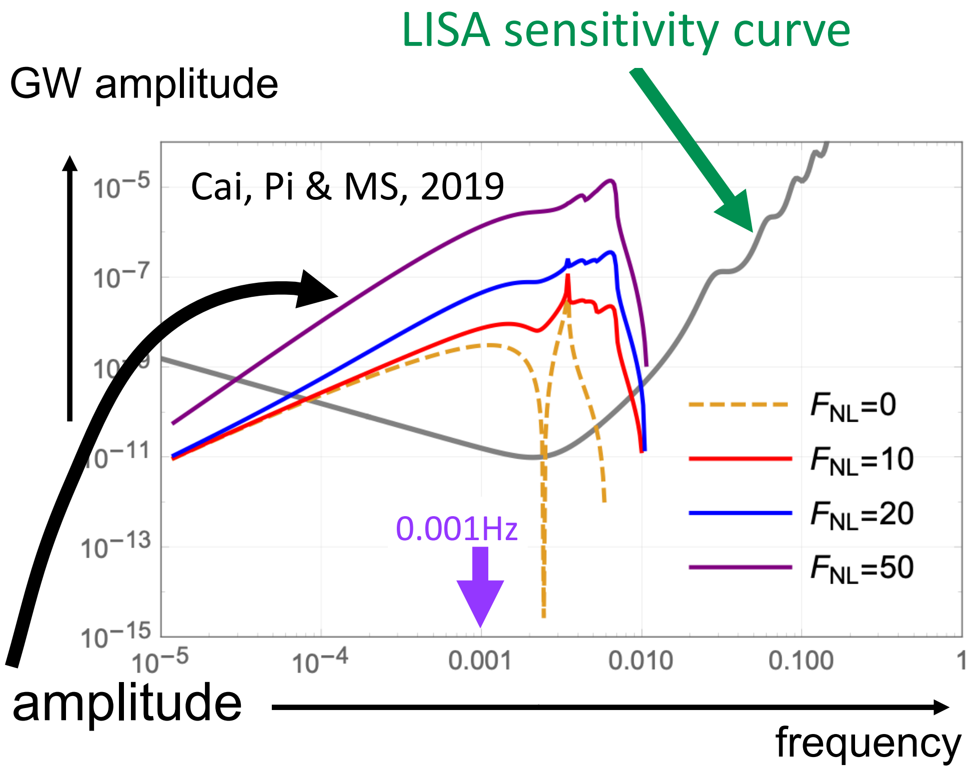
https://www.physics.unlv.edu/~jeffery/astro/relativity/gravitational_waves_low_frequency.html

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

Inflation as the base for exploring

Physics of the Early Universe

Era of

Observational/Experimental

Inflationary Cosmology!

Thank you for your attention

Cảm ơn sự chú ý của bạn

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