KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

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Inflation and Gravitational Wave Cosmology

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Inflation

What is Inflation?

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

- Inflation is a quasi-exponential expansion of the Universe at its very early stage; perhaps at $t \sim 10^{-34}$ 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.

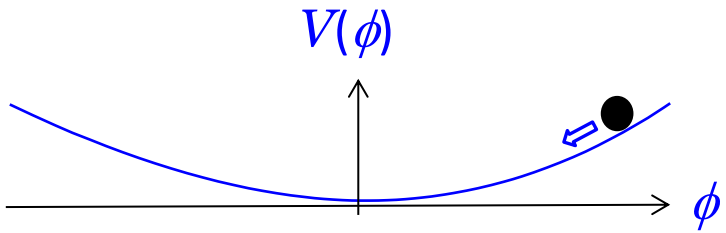
- Cosmic gravitational wave background is also generated.

Inflation in a nutshell

- Inflation is driven by a potential energy $V(\phi)$ of a scalar field ϕ

- ϕ evolves very slowly: $V \approx$ const. ➡ $\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \approx V(\phi)$

  (expansion induces effective friction ➡ friction-dominated, over-damped)



➡ energy density ρ remains almost constant in time

- Friedmann eq. (time-time component of Einstein eq.)

$3H^2 = 8\pi G\rho$ $\quad H = \frac{\dot{a}(t)}{a(t)}$: expansion rate of the Universe

cosmic scale factor $\quad$ Volume $\propto a^3$

- if ρ =const. , H =const. ➡ $a(t) \propto \exp[Ht]$

Volume expands exponentially = Inflation!

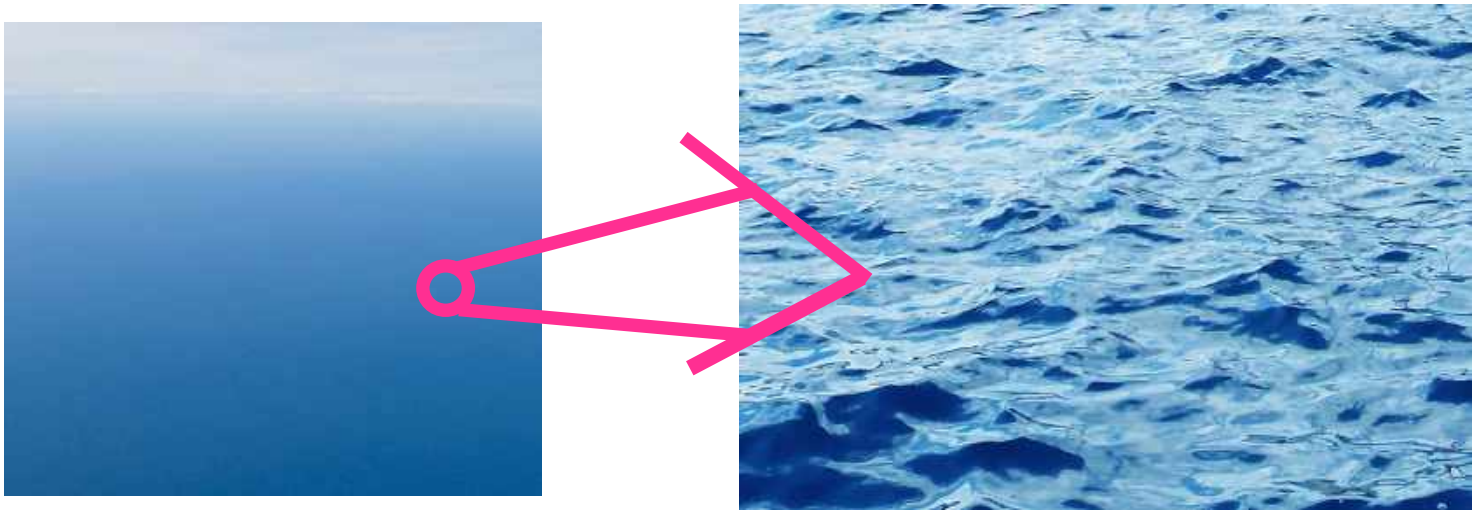
Quantum fluctuations in Inflationary Universe

vacuum fluctuations due to uncertainty principle $\Delta p \Delta x = \hbar$

$\hbar$=7x10^{-16} eV· s

they exist only on micro scales; never appear on macro scales

But,

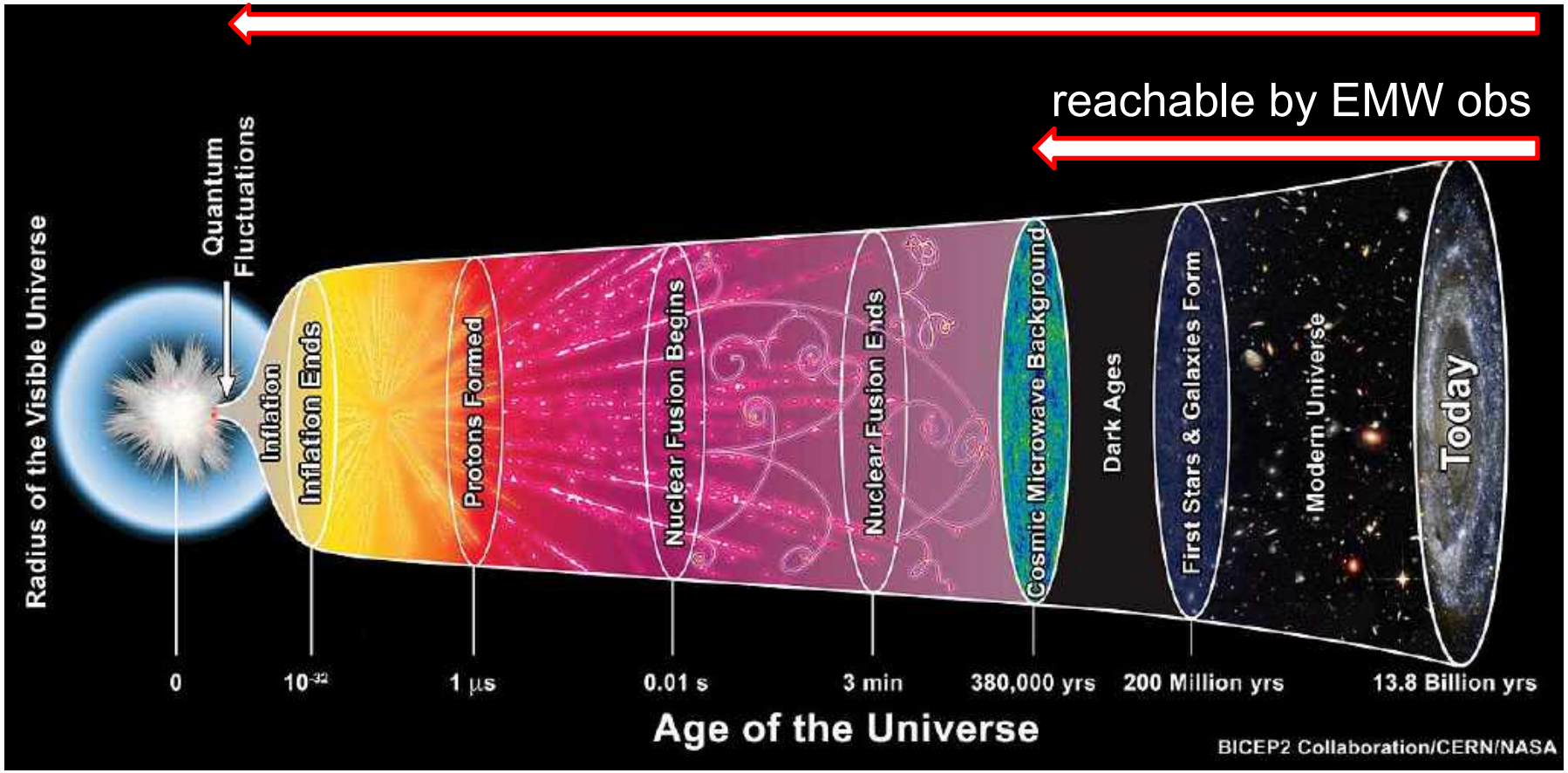


exponential expansion stretches vacuum fluctuations to macroscopic scales and fluctuations become frozen

$\Delta x \to \infty, \ \Delta p \to 0$

origin of all the structures (stars, life, etc.) in the Universe

Cosmological thermal history



Planck Cosmic Microwave Background Map

Planck 2015/2018

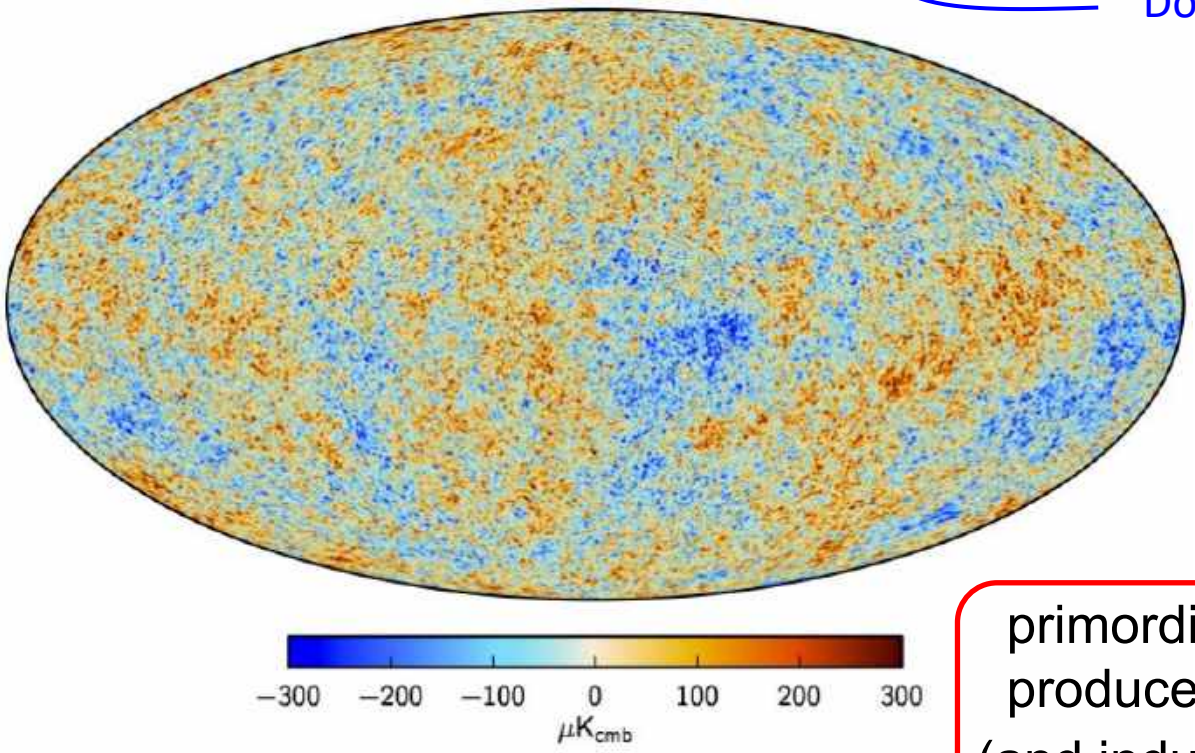
Sachs-Wolfe effect

gravitational redshift

but contains important info!

$$\frac{\Delta T}{T_0} = \frac{1}{3}\Psi - \boldsymbol{n}\cdot\boldsymbol{v} + (\text{small corrections}) \quad \sim 10^{-5}$$

Doppler effect



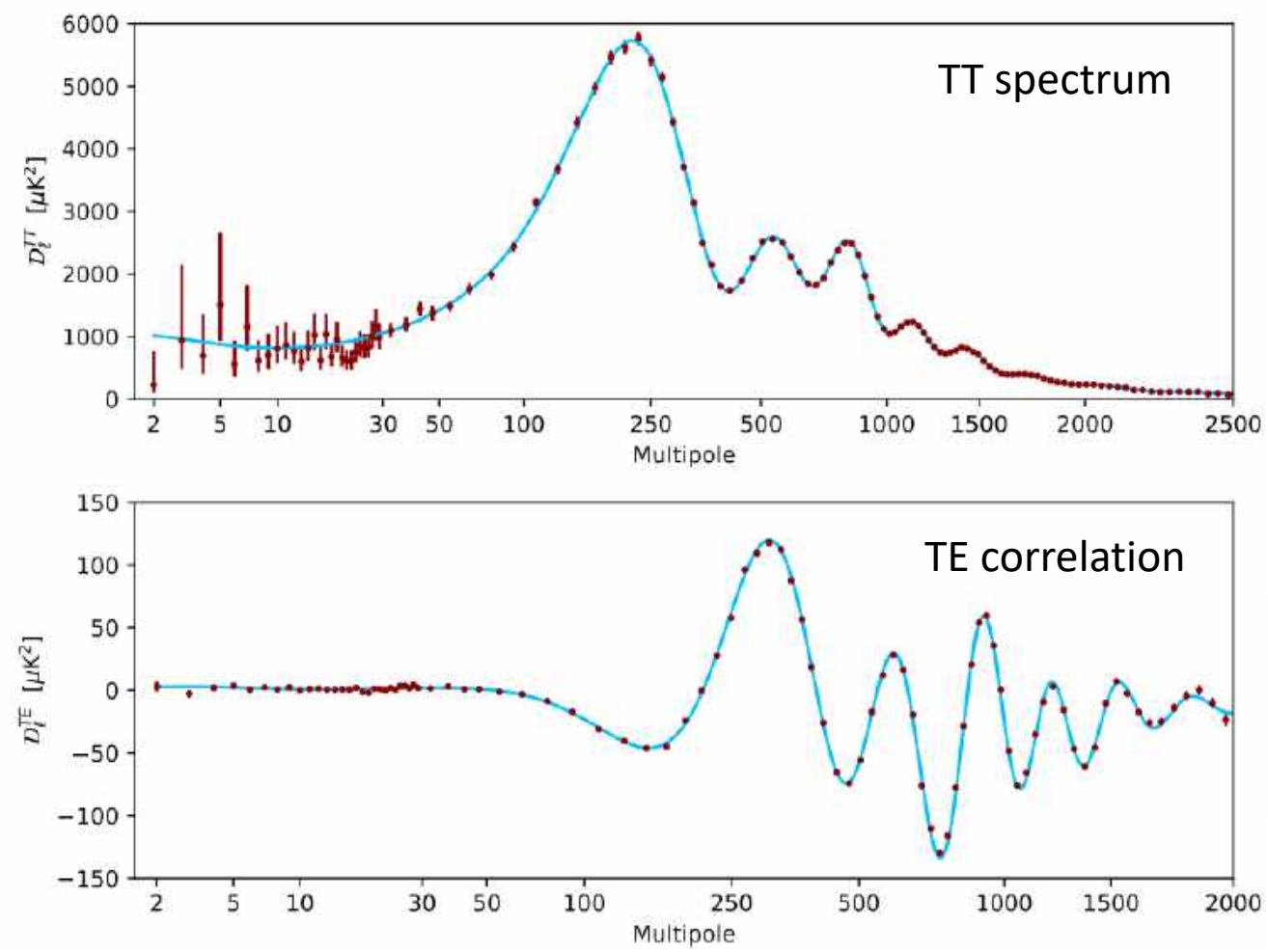
$$T_0 = 2.73\,K$$

primordial vacuum fluctuations produce Ψ and v

(and induce fluctuations in matter)

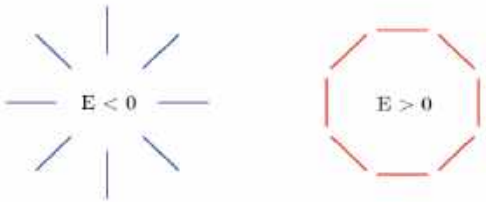
Planck CMB anisotropy spectrum

https://www.cosmos.esa.int/web/planck/picture-gallery



theory
(best fit model)

E: E-mode polarization



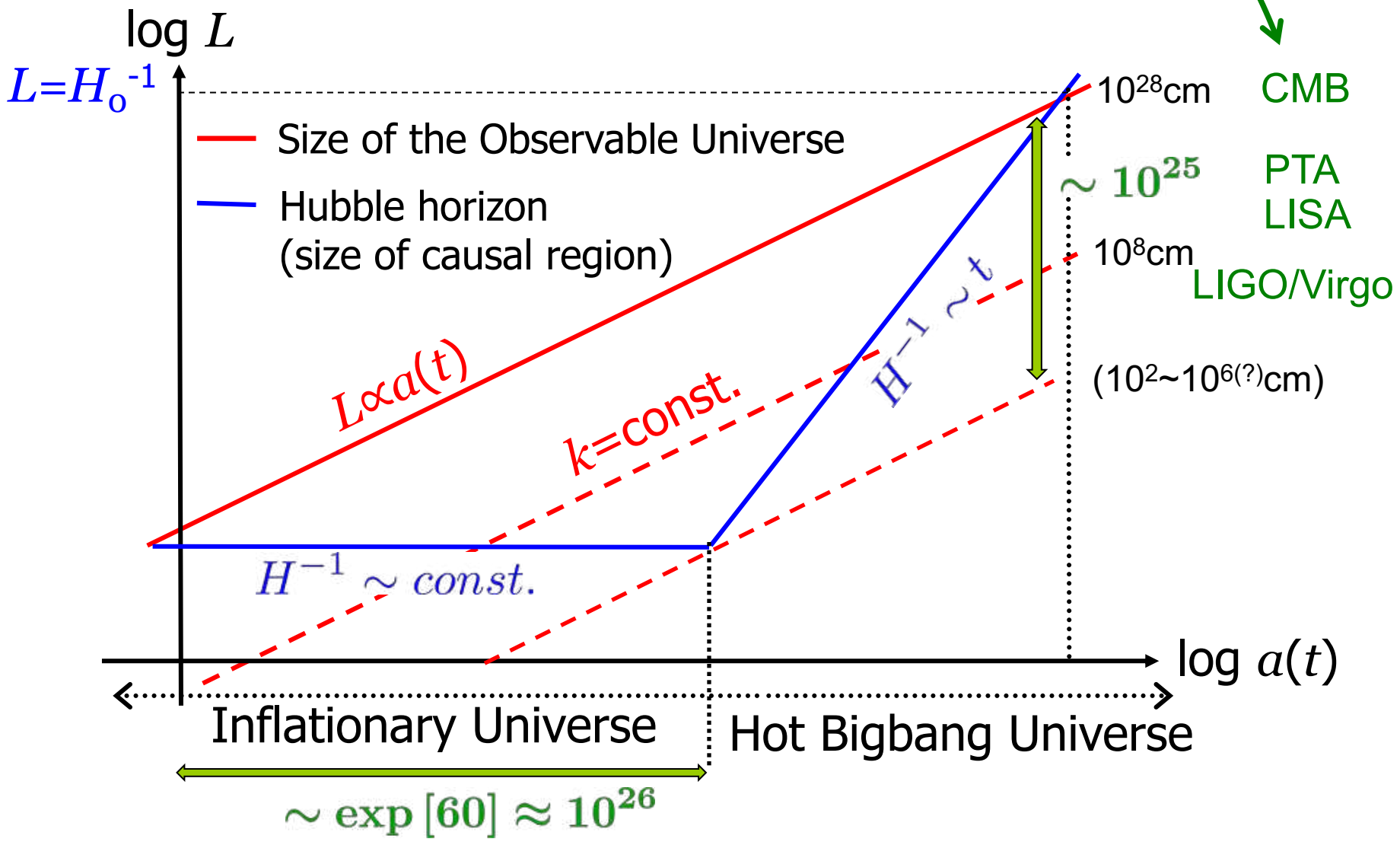
https://arxiv.org/abs/0811.3919

observational data perfectly agree with inflationary predictions

Inflation as GW source

length scales of the inflationary universe

⇔ targets for multi-frequency GW cosmology



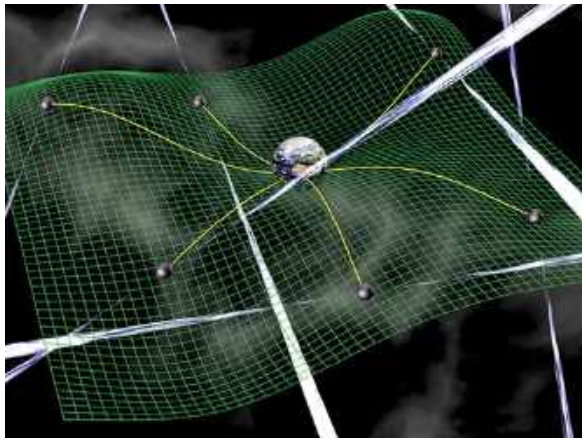
Current and future GW detectors

CMB B-mode: SP4, LiteBIRD…

$\sim 10^{-17}\mathrm{Hz}$

https://www.ipmu.jp/en/research-activities/research-program/LiteBIRD

Pulsar Timing Array (PTA)

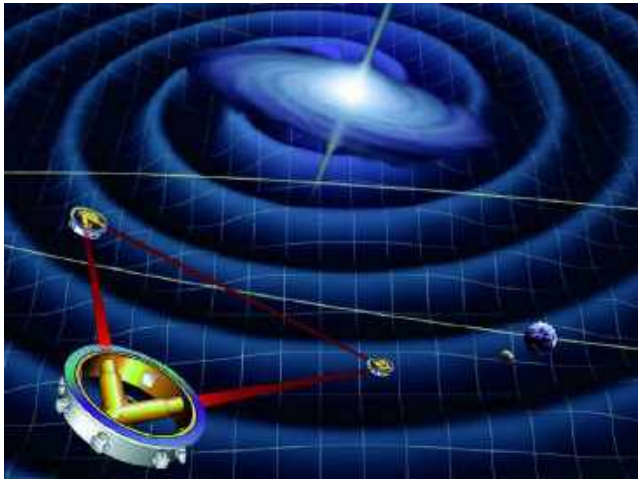


$\sim 10^{-8}\mathrm{Hz}$

credit: David Champion

Space-based IFO's: LISA, Taiji …

$\sim 10^{-3}\mathrm{Hz}$



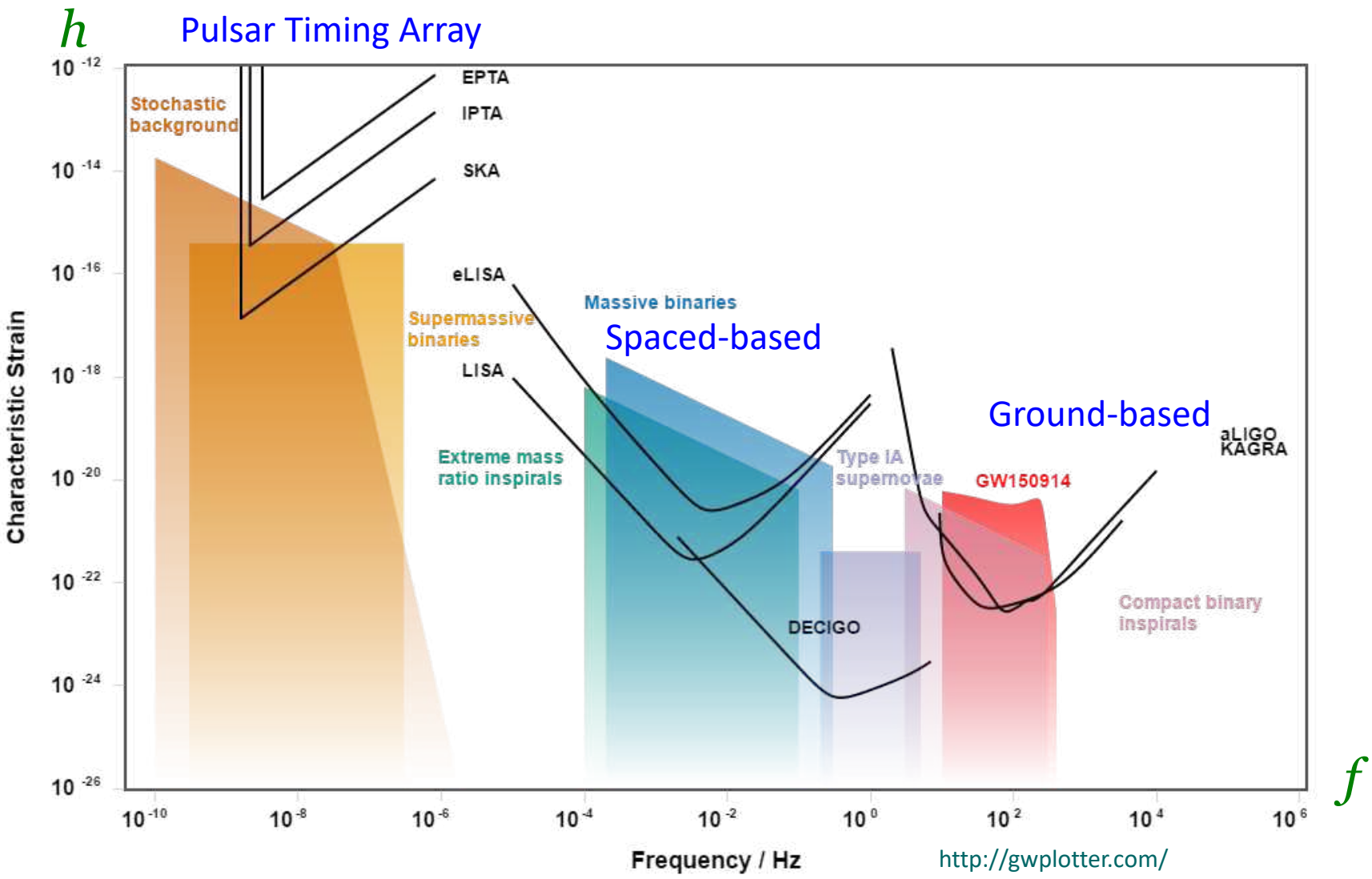
credit: ESA

Ground-based IFO's: LIGO/Virgo/KAGRA …

$\sim 10^{2}\mathrm{Hz}$

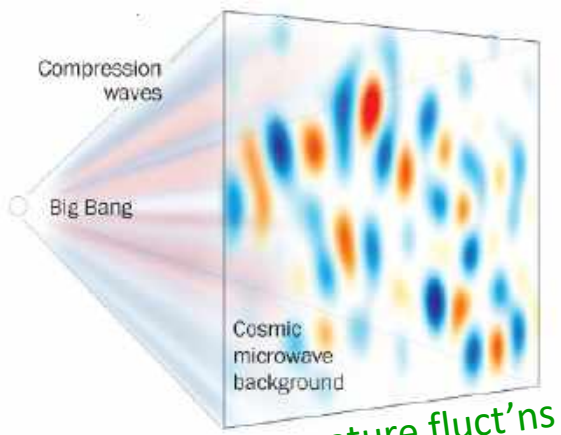
https://www.ligo.caltech.edu/

GWs: New window to explore the Unknown Universe!

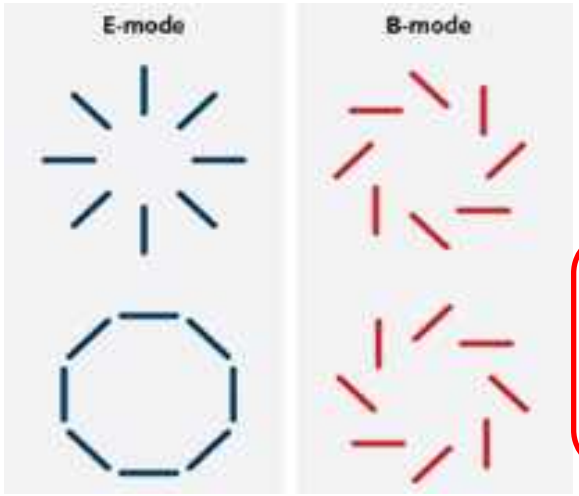


GWs from Inflation

- scalar field(s) produce density fluctuations
  -> CMB temp + E-mode
- tensor (GW) fluctuations
  -> CMB temp + E-mode + B-mode



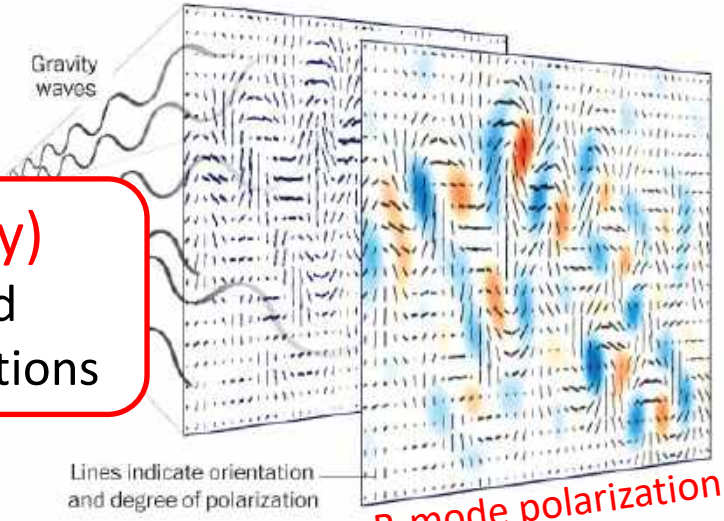
temperature fluct'ns



http://www.skyandtelescope.com/

E-mode (even parity)

B-mode (odd parity)
= cannot be produced
from density fluctuations

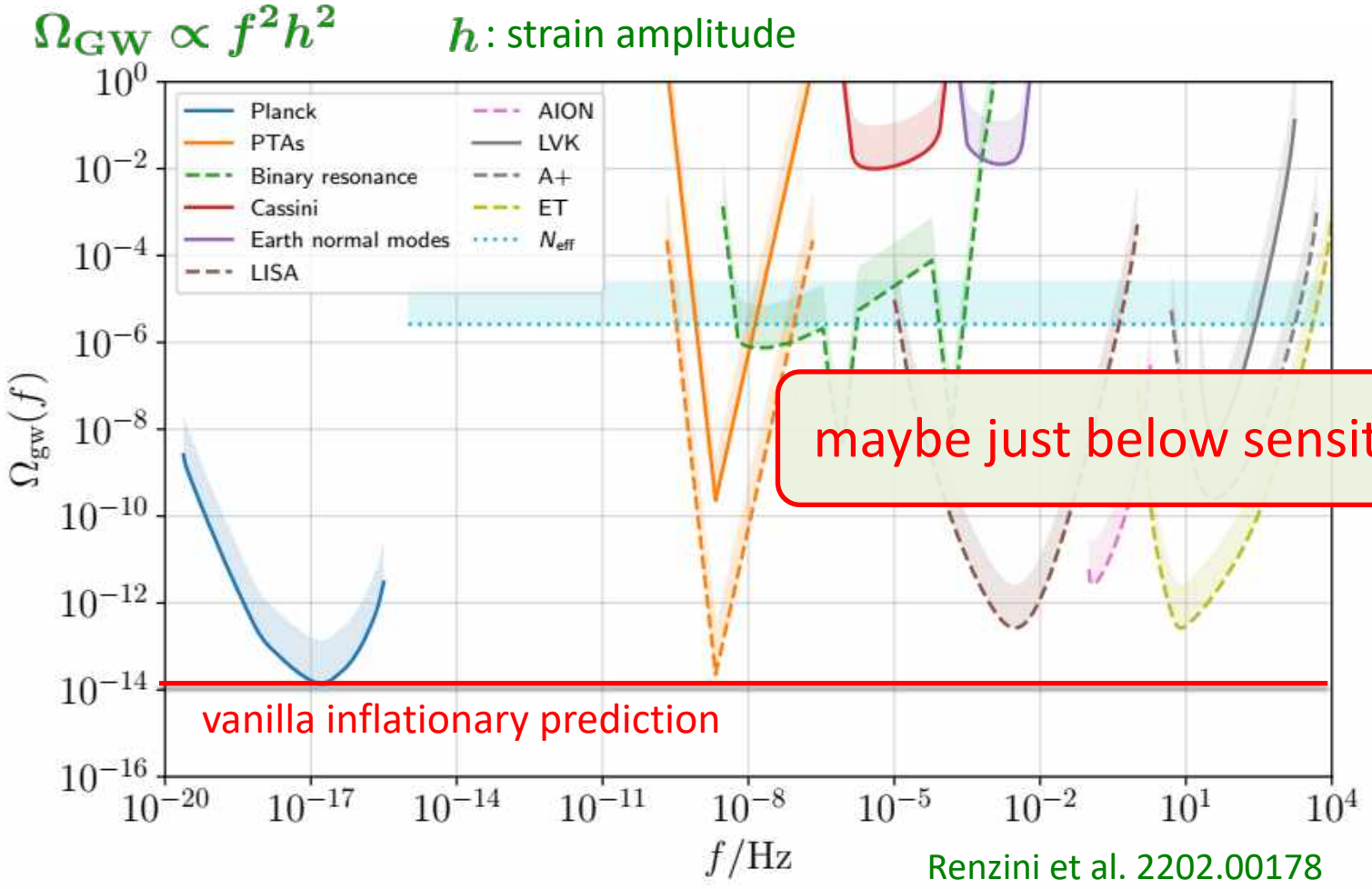


B-mode polarization
Harvard-Smithsonian Center for Astrophysics

CMB B-mode = cosmological GW detector!

GW spectrum from vanilla inflation

Can GWs from inflation be detected?



Blue-tilted GW spectrum?

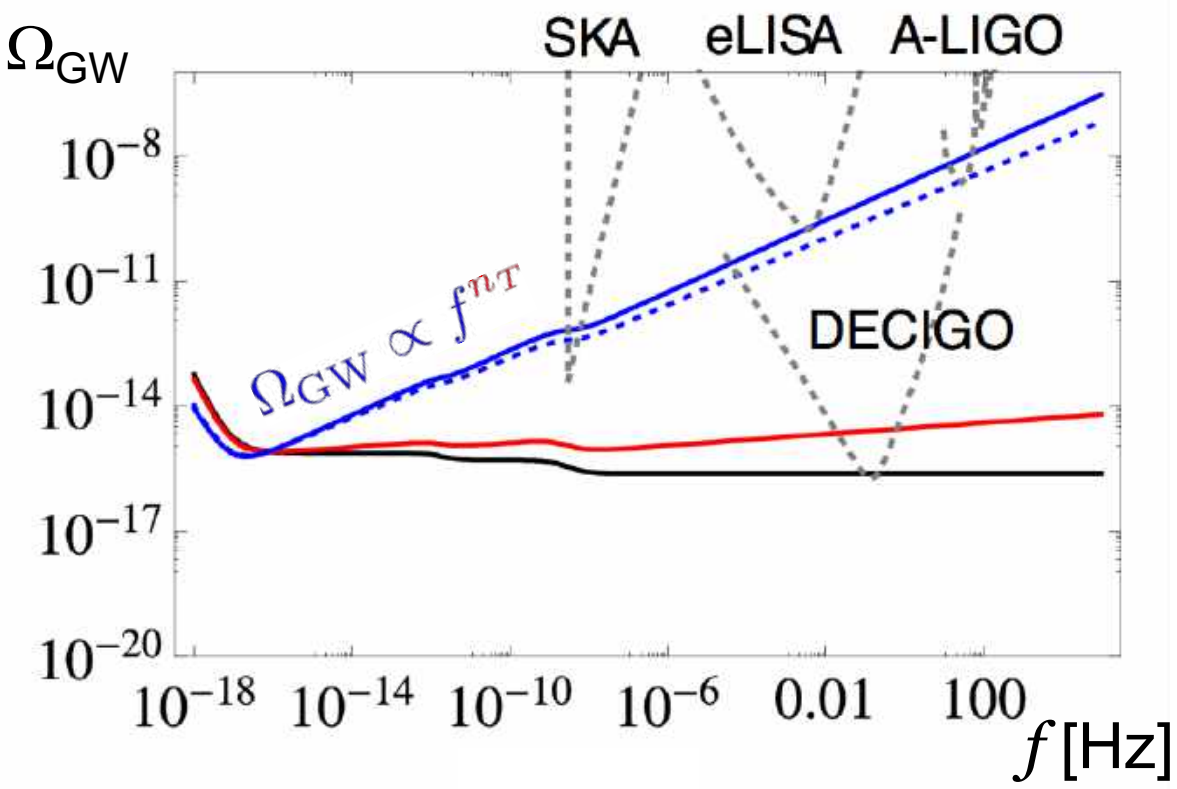
possible e.g. in massive gravity inflation model Lin & MS (2015)

m_g^2 : tensor mass during inflation = fcn of inflaton ϕ

spectral index:

$$n_T = \frac{2m_g^2}{3H^2}$$

- : $m_g^2 / H^2 = 0.6$
- : $m_g^2 / H^2 = 0.1$
- : $n_T = 0$



➢ many other models that produce detectable GWs exist

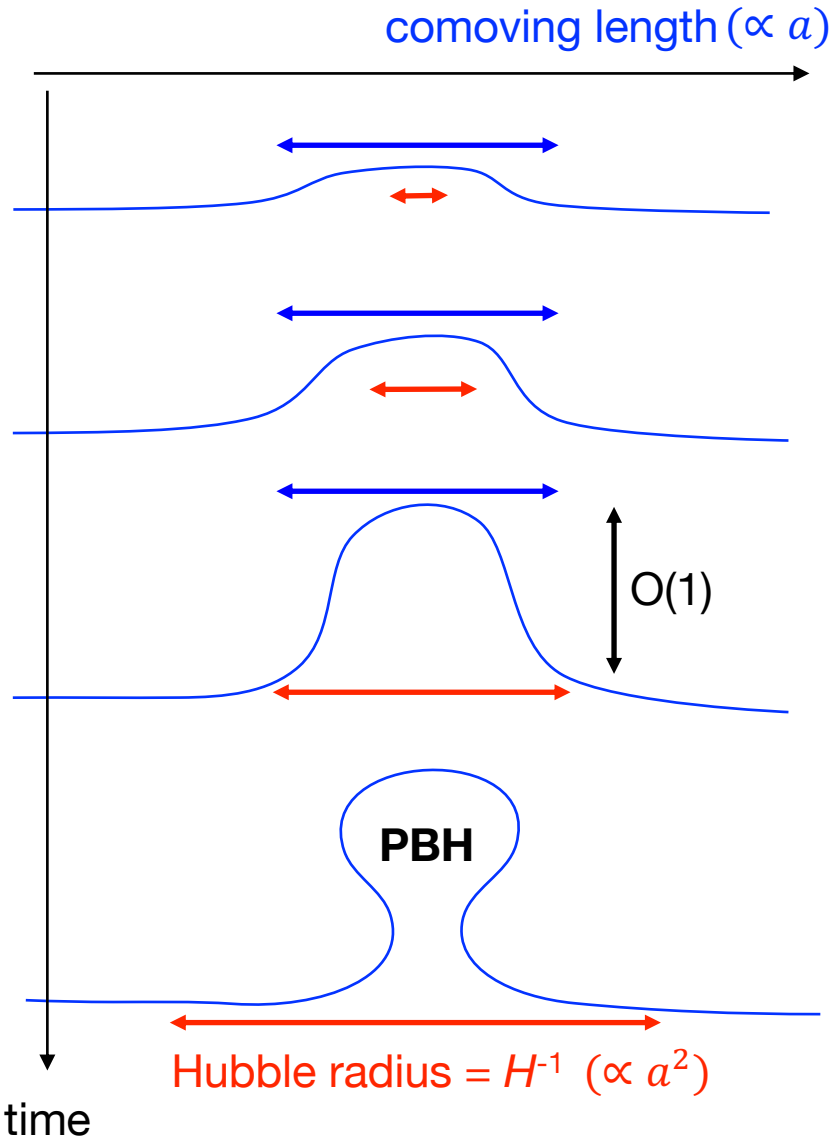
e.g., review by Caprini & Figueroa 2018

Primordial Black Holes and induced GWs

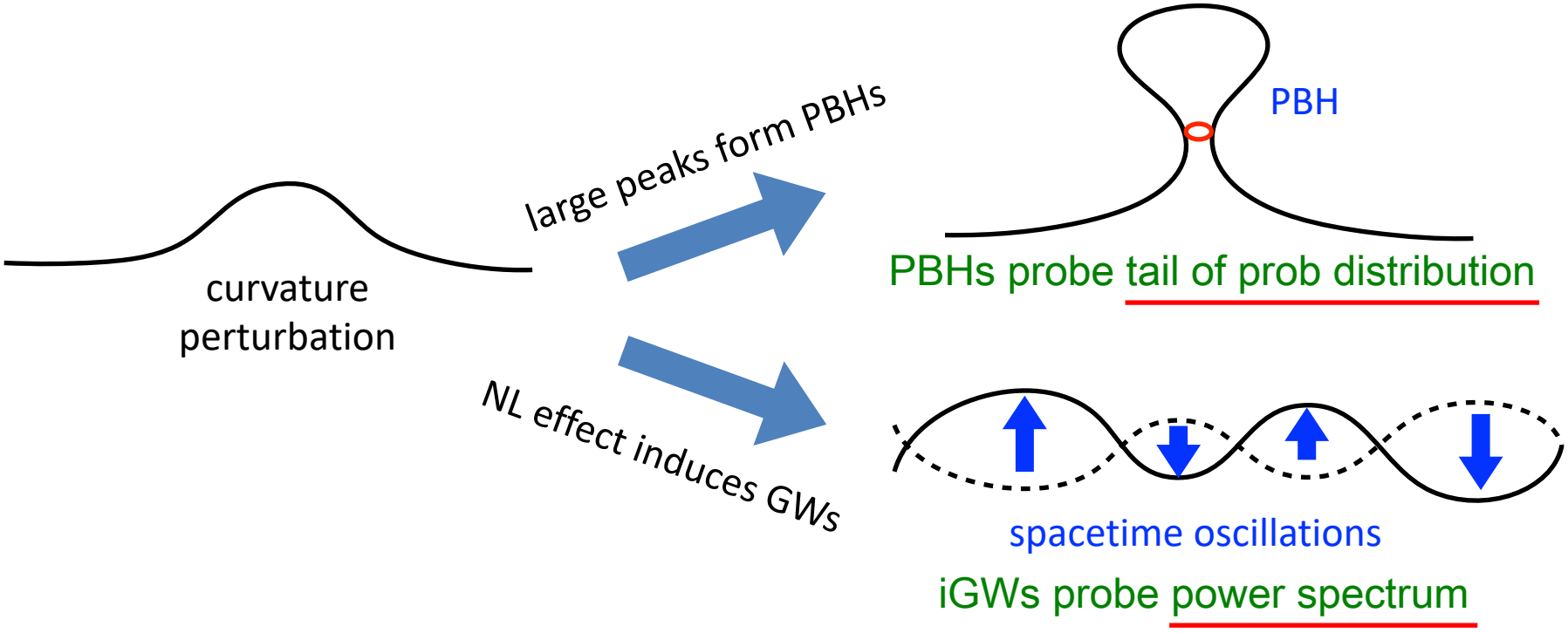
PBH formation in a nutshell

- PBHs are those formed in the very early universe, conventionally when the universe was radiation-dominated. Hawking '71, Carr & Hawking '74
- Presumably they originate from a large positive curvature perturbation produced during inflation (which hence should be a rare event).
- For a BH to form, the perturbation amplitude must be O(1) on the Hubble horizon scale.

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



iGWs can capture PBHs!



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

CDM=Cold Dark Matter

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

LV=LIGO-Virgo

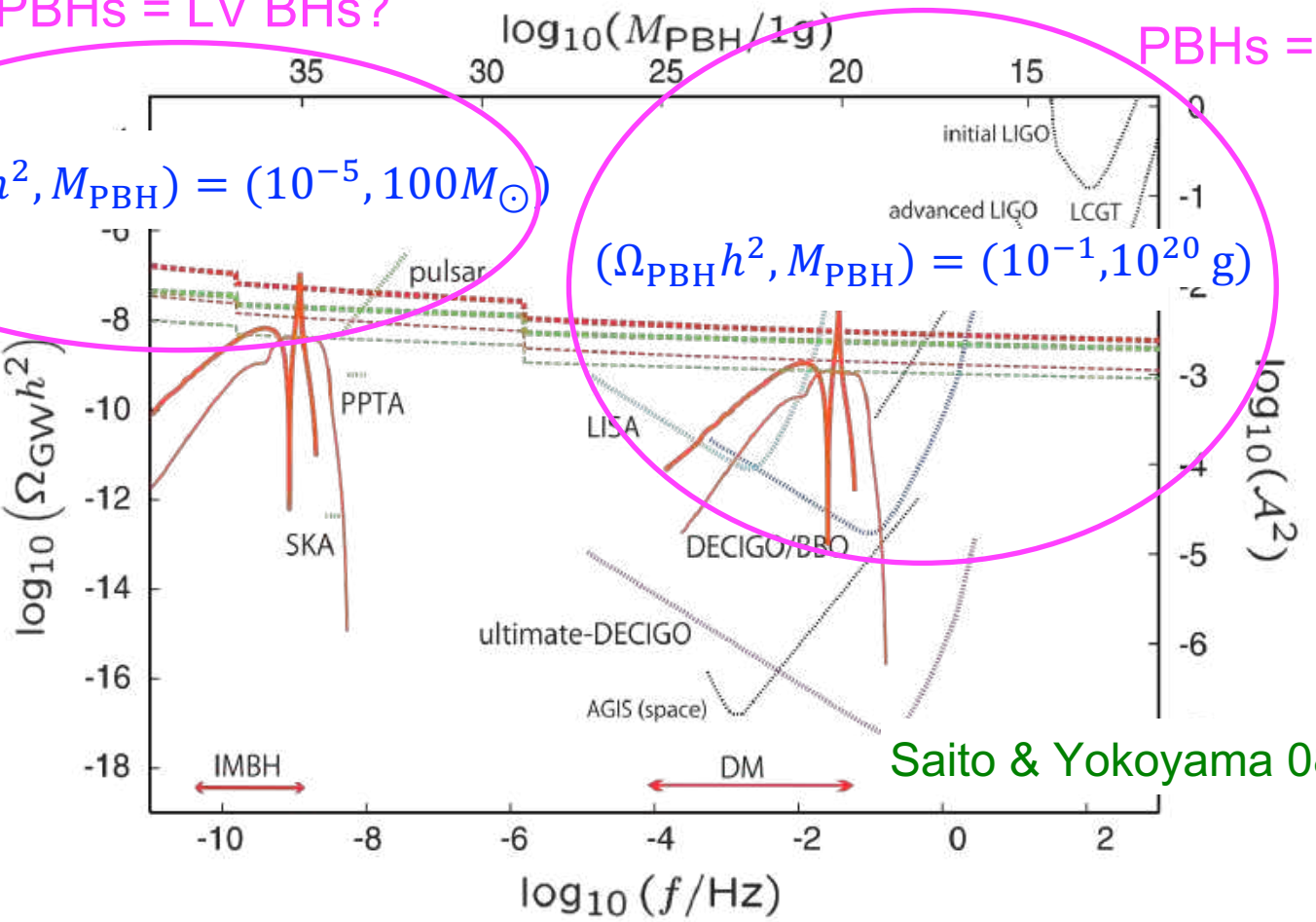
GWs can test PBH scenario!

PBHs = LV BHs?

$(\Omega_{\rm PBH}h^2, M_{\rm PBH}) = (10^{-5}, 100M_\odot)$

PBHs = CDM?

$(\Omega_{\rm PBH}h^2, M_{\rm PBH}) = (10^{-1}, 10^{20}\,{\rm g})$



Saito & Yokoyama 0812.4339

- PBHs = LV BHs scenario is already constrained by NANOGrav (PTA)

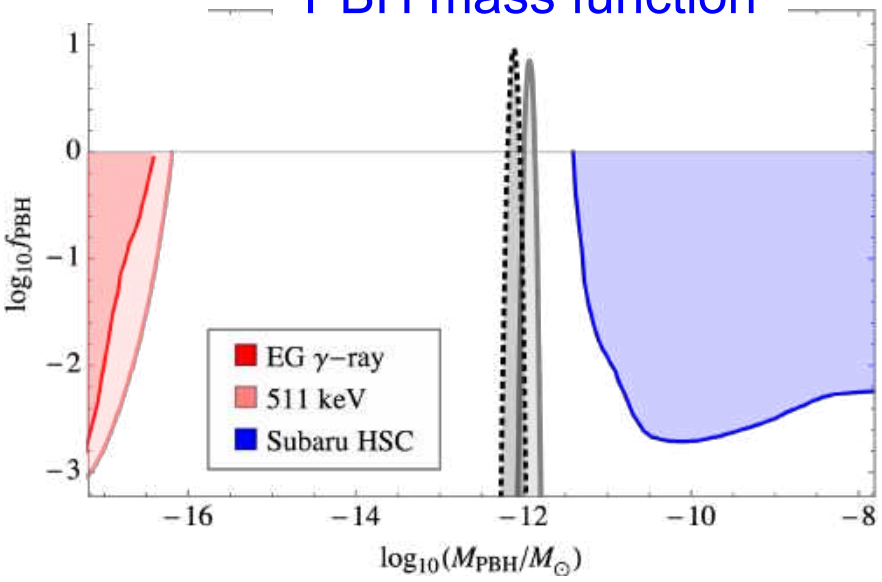
Cai, Pi, Wang & Yang 1907.06372

iGWs in non-minimal curvaton model

Pi & MS, 2112.12680

fraction in CDM

PBH mass function



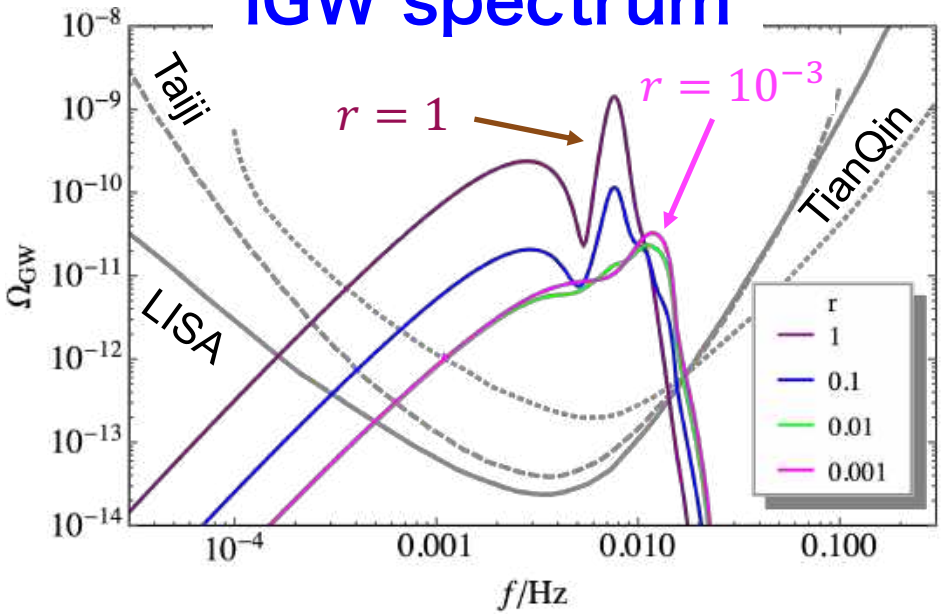
peak: $M_{\rm PBH} \sim 10^{21}{\rm g}$

$\Updownarrow$

$R_{\rm BH} \sim 10^{-7}{\rm cm}$

The model predicts a highly non-Gaussian tail in PDF for the curvature perturbation

iGW spectrum



PBH=CDM scenario can be clearly verified or falsified by LISA!

r <<1 = stronger non-Gaussianity

Summary

* Inflation has become the standard model of the Universe
* Cosmological GWs are the key to confirmation of inflation
* Era of multi-band GW cosmology has begun!

CDM may be PBHs!

future GW detectors will prove/disprove the scenario.

* Entire stage of inflation may be probed by GWs
* Astrophysical GWs also play essential roles

GWs will be an essential tool to explore the Physics of the Unknown Universe!

Stay tuned!

Thank you!