KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

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Primordial Black holes from Inflation and Gravitational Waves

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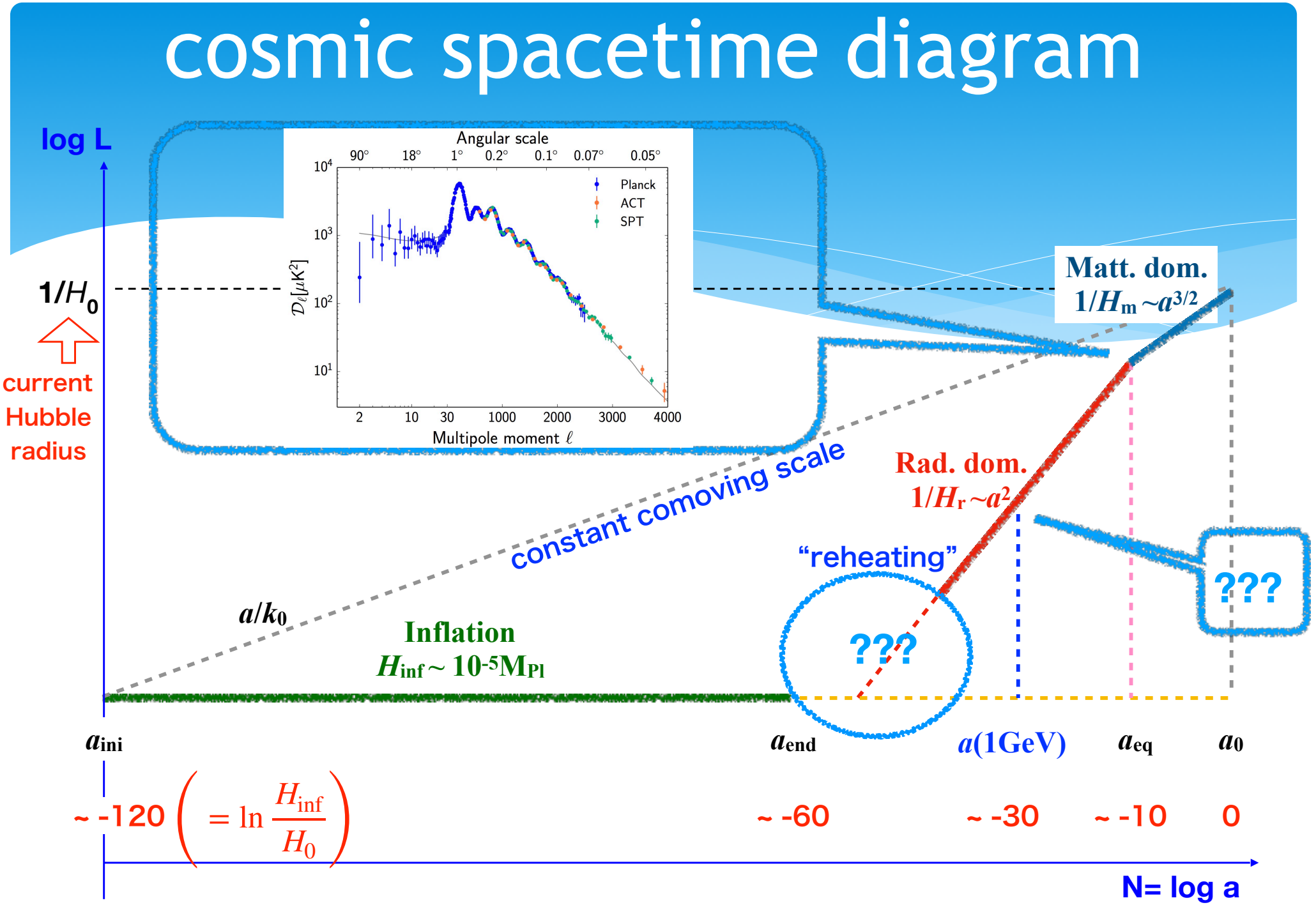
Inflation & PBH formation

cosmic spacetime diagram



curvature perturbation from inflation

- inflaton (~massless) vacuum fluctuations (=Gaussian)

$$\left|\left\langle \phi \middle| \vec{k} \right\rangle\right|^2 = \left|\varphi_k\right|^2, \quad \varphi_k \sim \frac{1}{\sqrt{2w_k}} e^{-iw_k t} \; ; \quad w_k = \frac{k}{a} \gg H$$

rapid expansion renders oscillations frozen at $k/a < H$

(fluctuations become "classical" on superhorizon scales)

$$\varphi_k \sim \frac{H}{\sqrt{2k^3}} \; ; \quad \frac{k}{a} \ll H \;\Rightarrow\; \left\langle \delta\phi_k^2 \right\rangle = \left(\frac{H}{2\pi} \right)^2_{k/a \sim H}$$

··· almost scale-invariant

for $\epsilon = -\frac{\dot{H}}{H^2} \ll 1$

- curvature perturbation on comoving slices

$$\mathcal{R}_c = -\frac{H}{\dot{\phi}} \delta\phi$$

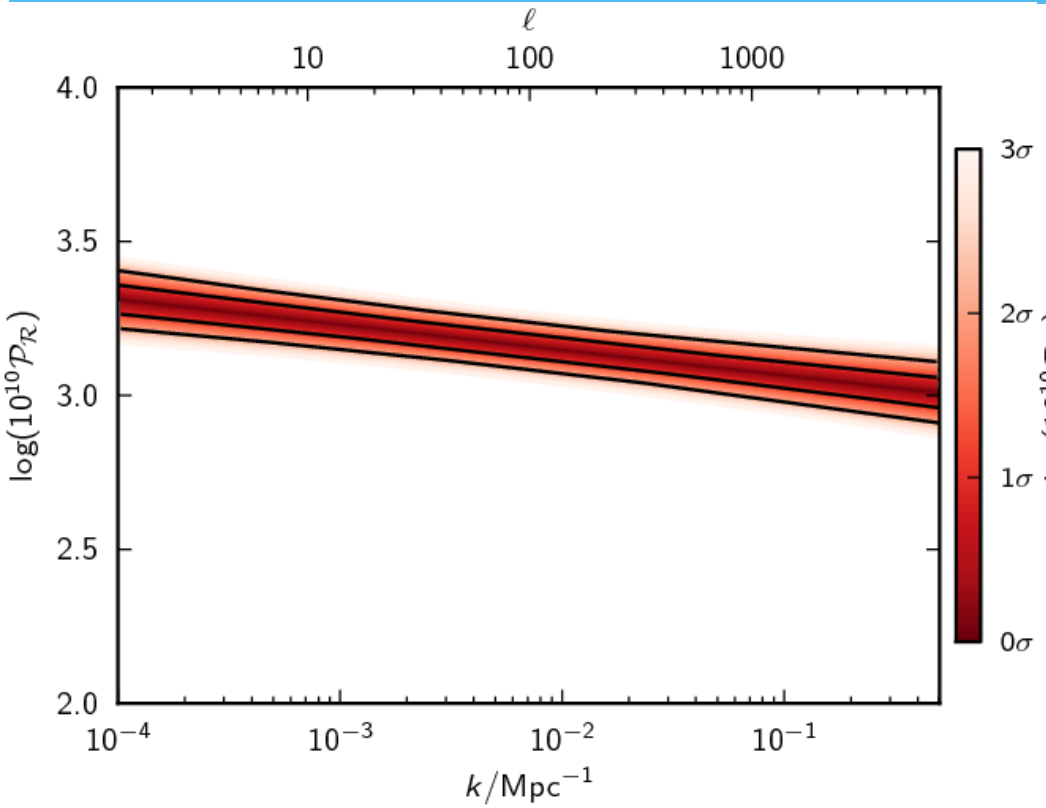
··· conserved on superhorizon scale

for single-field slow-roll models

(almost scale-invariant if $\dot{\phi}$ is also slowly varying)

observational constraint on inflation

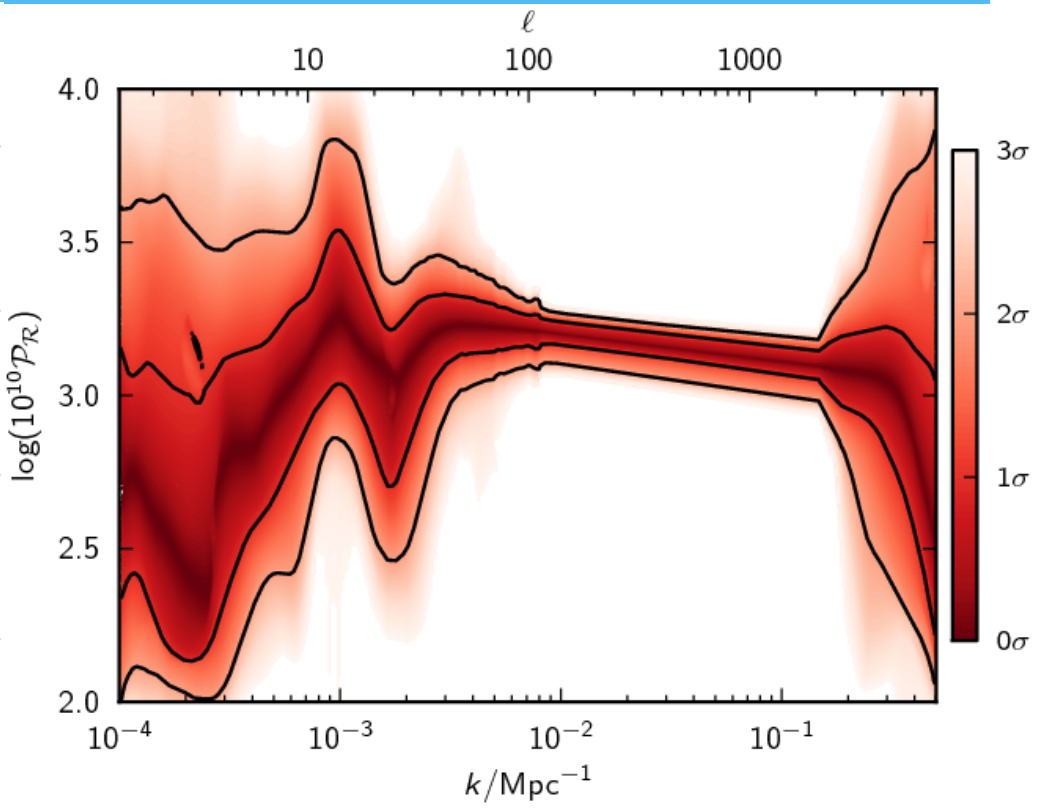
Planck 2015 results XX



power-law

$$\mathcal{P}_{\mathcal{R}} = A(k/k_*)^{n_s-1}$$

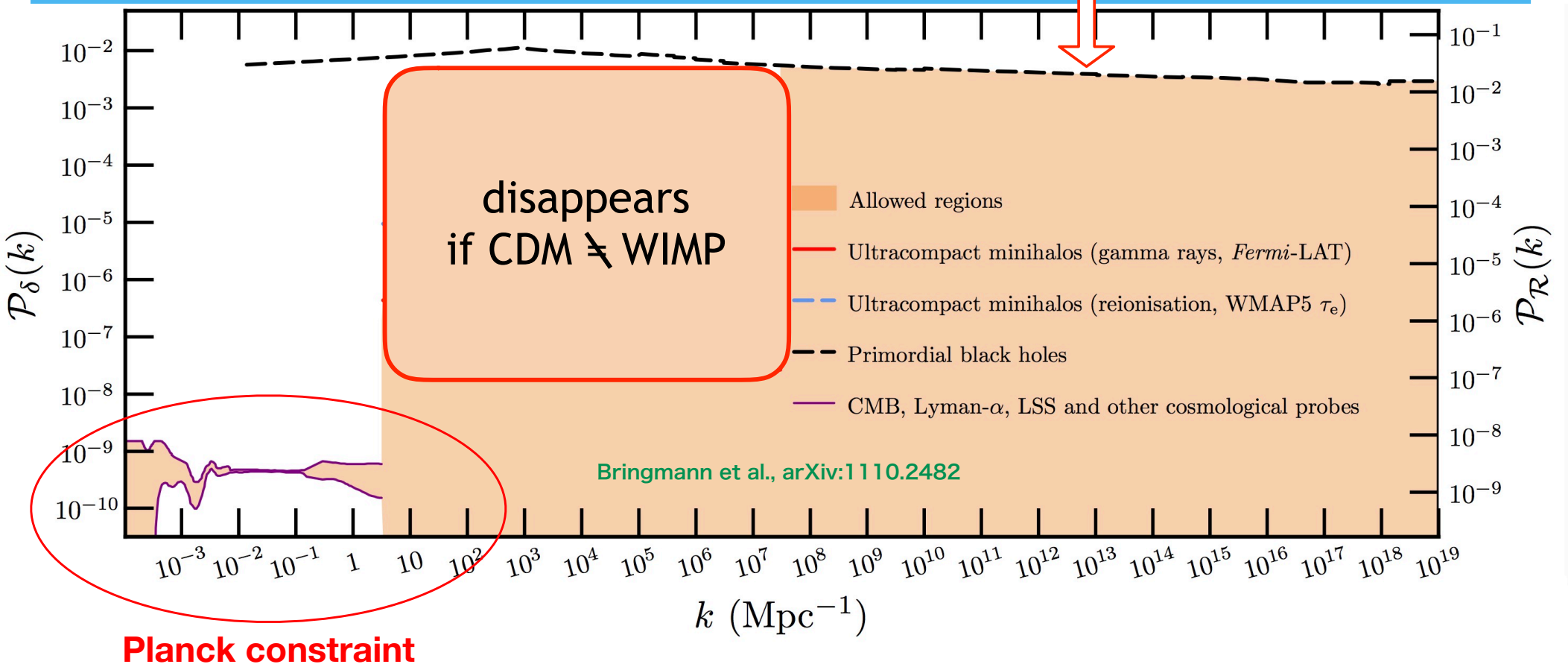
$n_s \approx 0.968$ ⋯ almost scale-invariant



piece-wise continuous
(9 segments)

observational constraint on inflation

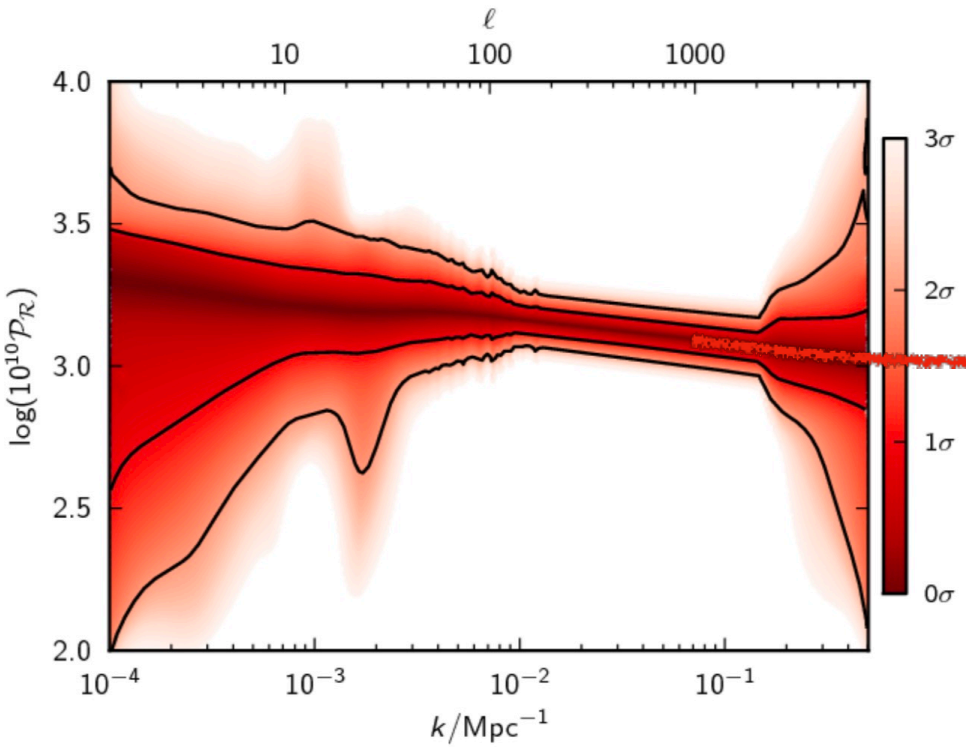
constraints on small scales are from BHs



Planck constraint

There are some constraints on small scales, but quite weak.

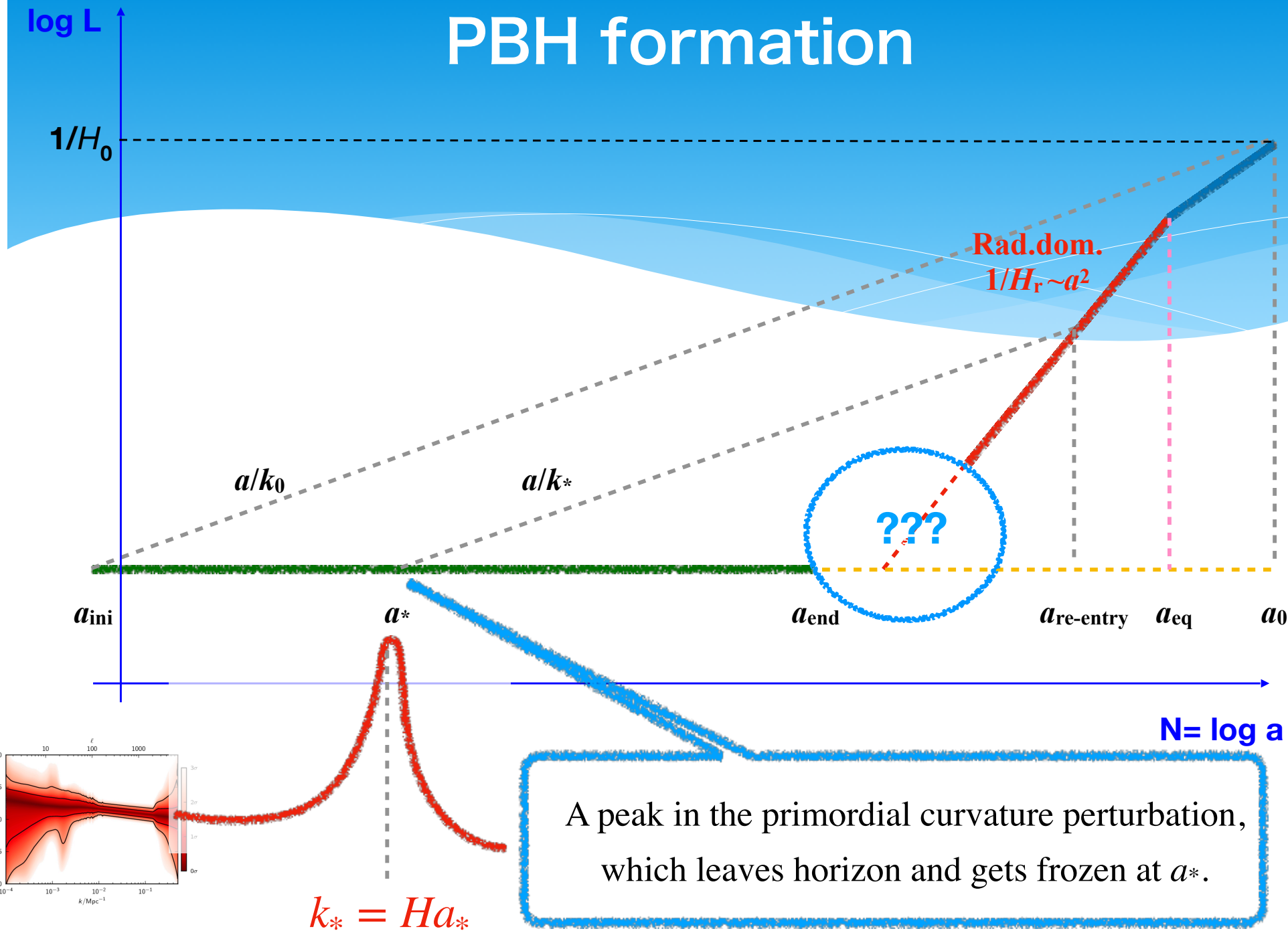
Bayesian reconstruction of the primordial power spectrum with $l < 2300$. (Planck 2015)



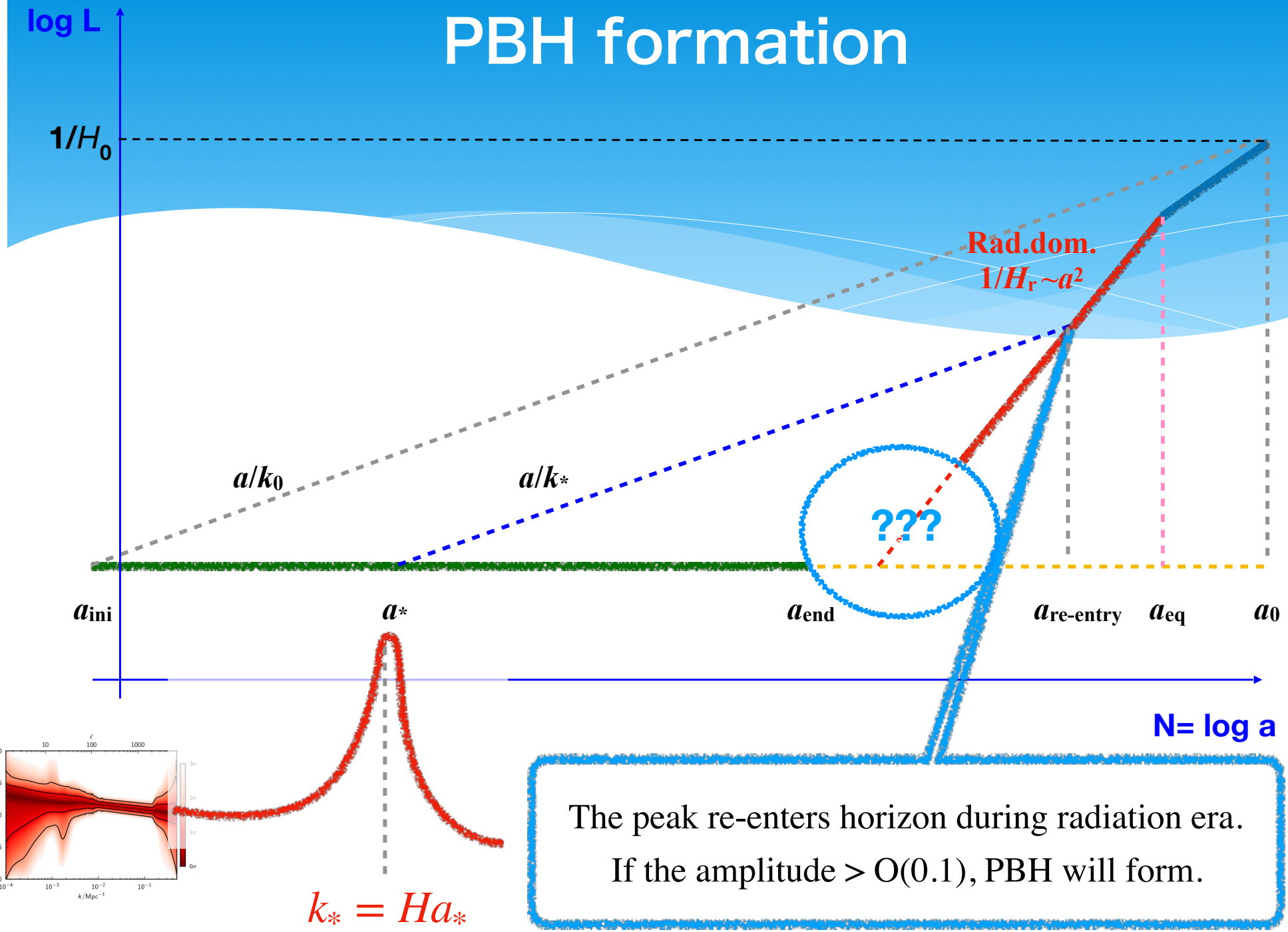
?

No resolution to say anything precise about higher *k*.

PBH formation



PBH formation

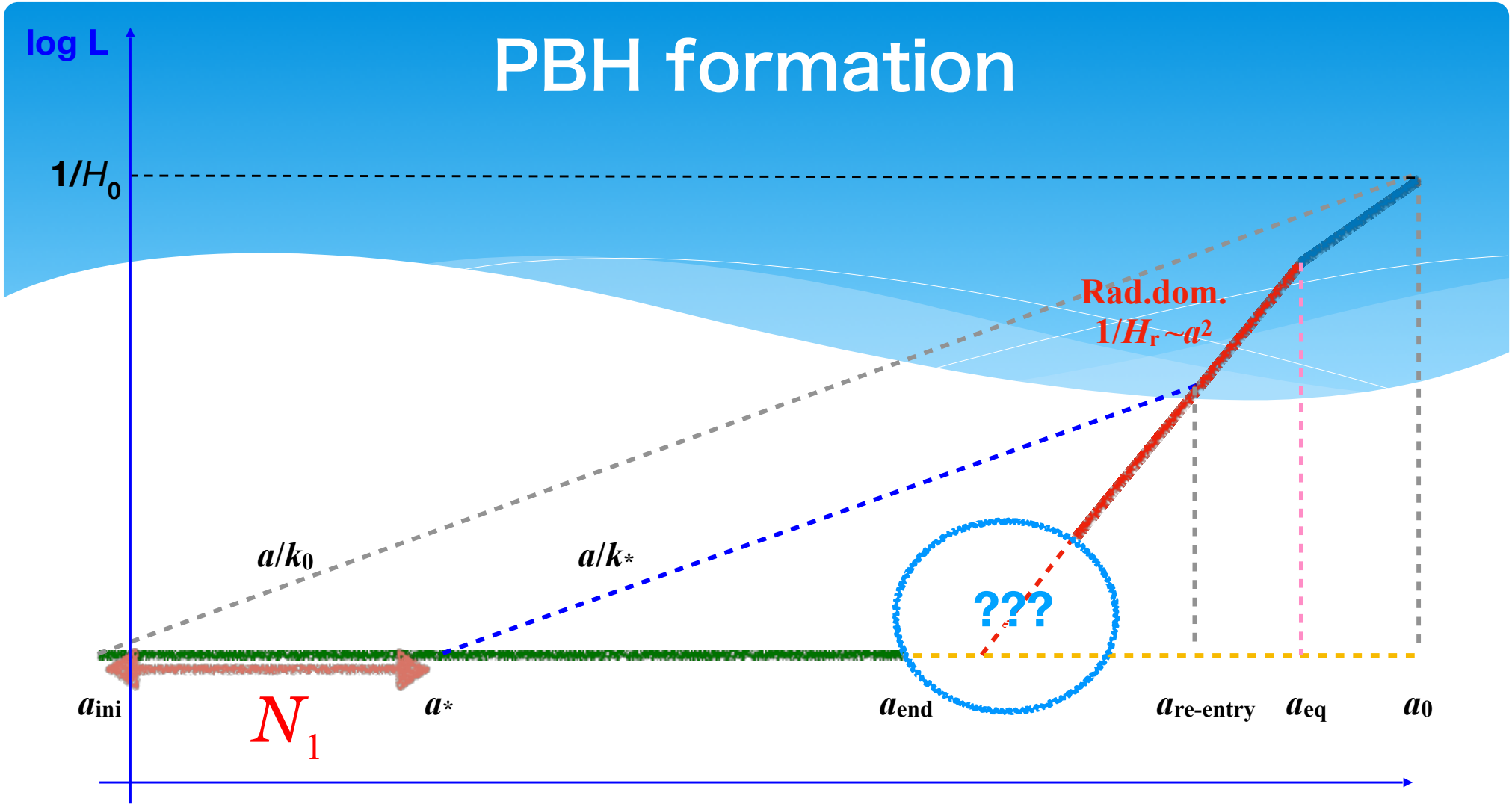


$k_* = Ha_*$

The peak re-enters horizon during radiation era.

If the amplitude > O(0.1), PBH will form.

PBH formation



PBH mass: $M_{PBH} = \gamma M_H \sim \frac{M_{Pl}^2}{H} = 10^{58} M_{Pl} e^{-2N_1} = M_{Pl} 10^{58-0.87N_1}$

Inverse relation: $N_1 = 44.4 - \frac{1}{2}\ln\left(\frac{M_{PBH}}{10^{16}\,\mathrm{g}}\right)$

PBH mass scale does NOT depend on the reheating physics

Primordial Black Holes

What are Primordial BHs?

- PBH = BH formed before recombination epoch (ie at z >>1000)
  conventionally during radiation-dominated era
- Hubble size region with $\delta\rho/\rho$=O(1) collapses to form BH

  Carr (1975), ….
- Such a large perturbation may be produced by inflation

  Carr & Lidsey (1991), …
- PBHs may dominate Dark Matter.

  Ivanov, Naselsky & Novikov (1994), ...
- Supermassive BHs $\left(M \gtrsim 10^6 M_\odot\right)$ may originate from PBHs.

  Bean & Magueijo (2002), ...
- ….

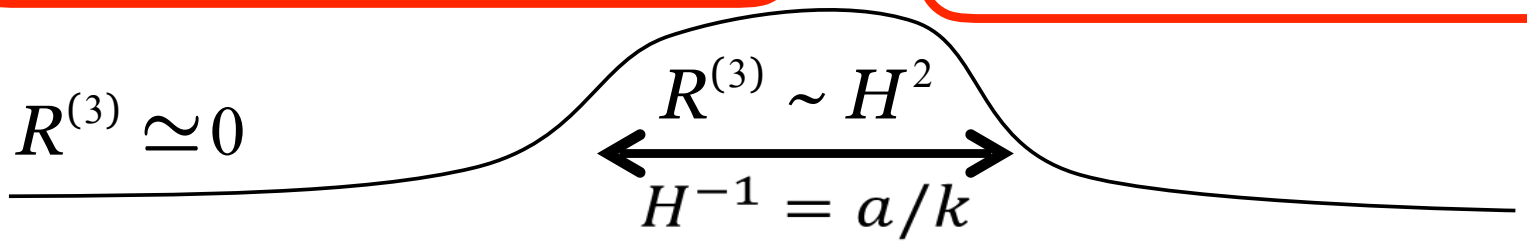
Curvature perturbation to PBH

➢ gradient expansion/separate universe approach

$$6H^2(t,x) + R^{(3)}(t,x) = 16\pi G\rho(t,x) + \cdots$$

Hamiltonian constraint (Friedmann eq.)

$$R^{(3)} \approx -\frac{4}{a^2}\nabla^2\mathcal{R}_c \approx \frac{8\pi G}{3}\delta\rho_c \quad \Rightarrow \quad \frac{\delta\rho_c}{\rho} \approx \mathcal{R}_c \ \text{ at } \ \frac{k^2}{a^2} = H^2$$



➢ If $R^{(3)} \sim H^2$ $(\Leftrightarrow \delta\rho_c/\rho \sim 1)$ it collapses to form BH

Young, Byrnes & MS '14

$$M_{\rm PBH} \sim \rho H^{-3} \sim 10^5 M_\odot \left(\frac{t}{1s}\right) \sim 20 M_\odot \left(\frac{k}{1{\rm pc}^{-1}}\right)^{-2}$$

➢ Spins of PBHs are expected to be very small

examples

hybrid-type inflation

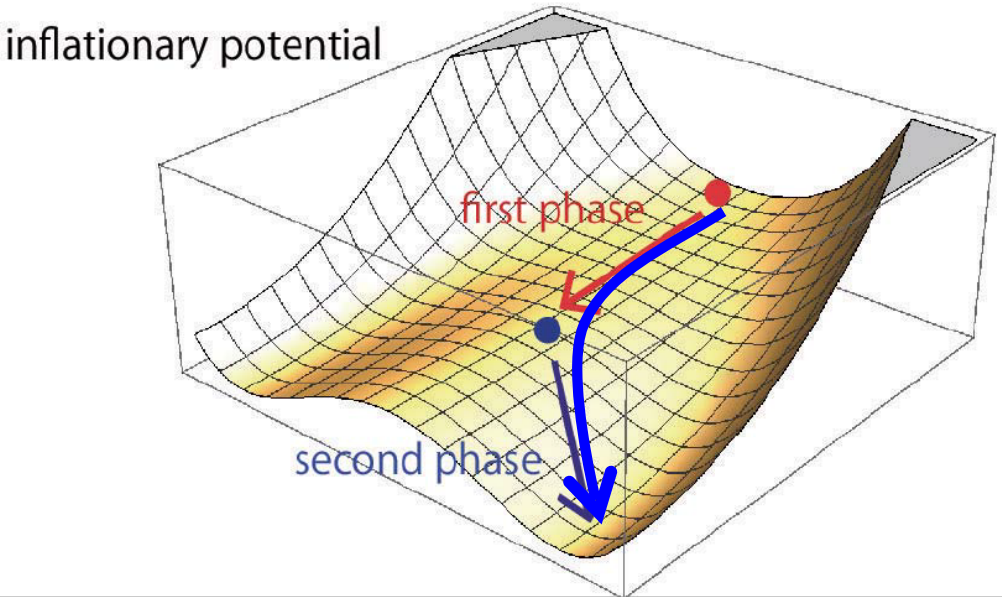
Garcia-Bellido, Linde & Wands '96, …

$\mathcal{R}_C$ grows near the saddle point

non-Gauss may become large

Abolhasani, Firouzjahi & MS '11,..

Pattison et al. 1707.00537

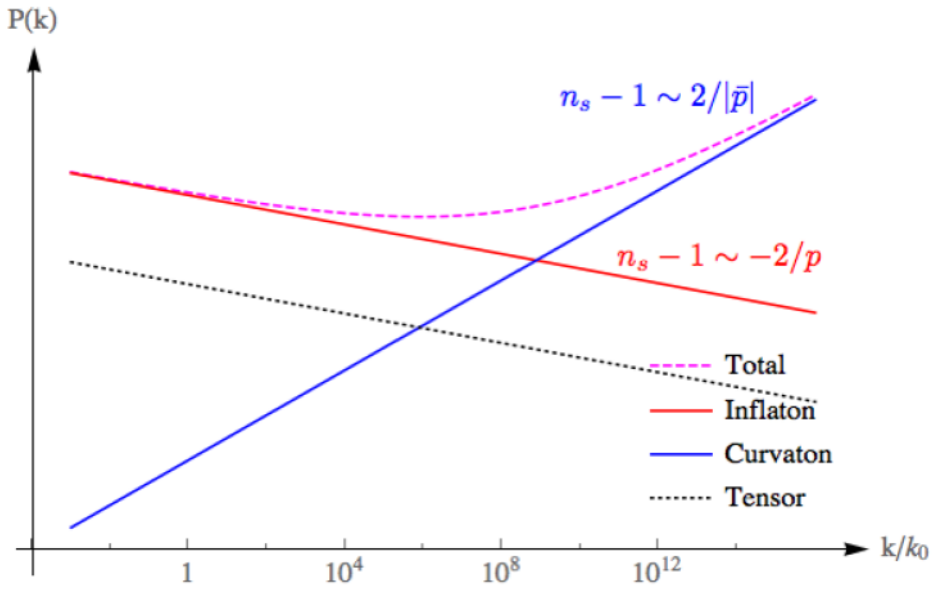


non-minimal curvaton

Domenech & MS '16

$$L = -\frac{1}{2} f(\phi) g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi$$

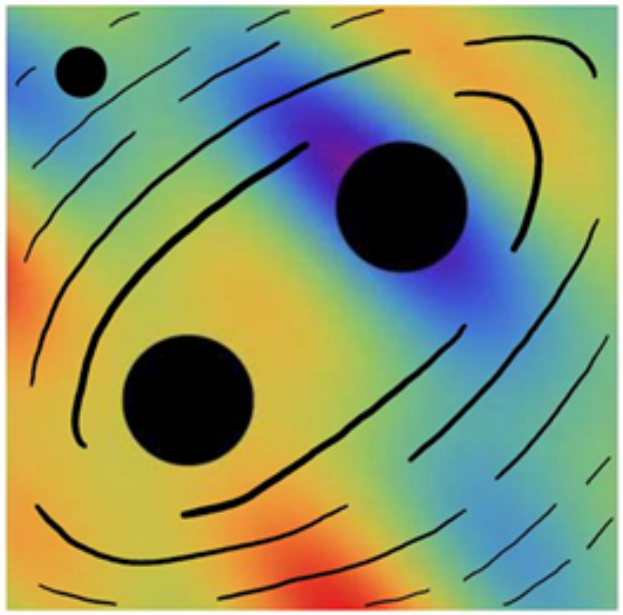
$$-\frac{1}{2} h(\phi) m^2 \chi^2$$



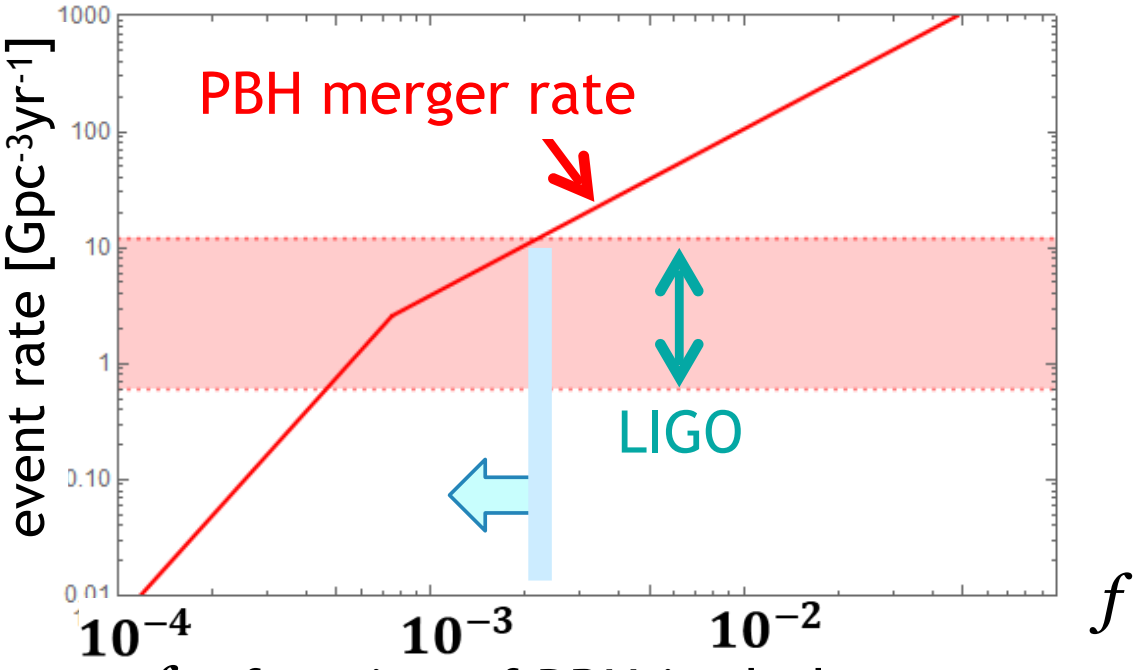
LIGO BHs = PBHs?

MS, Suyama, Tanaka & Yokoyama '16

$$M_{PBH} \simeq 20\left(\frac{k}{\mathrm{kpc}^{-1}}\right)^{-2} M_\odot \simeq 20\left(\frac{100\mathrm{MeV}}{T}\right)^{2} M_\odot$$



3-body interaction leads to formation of BH binaries

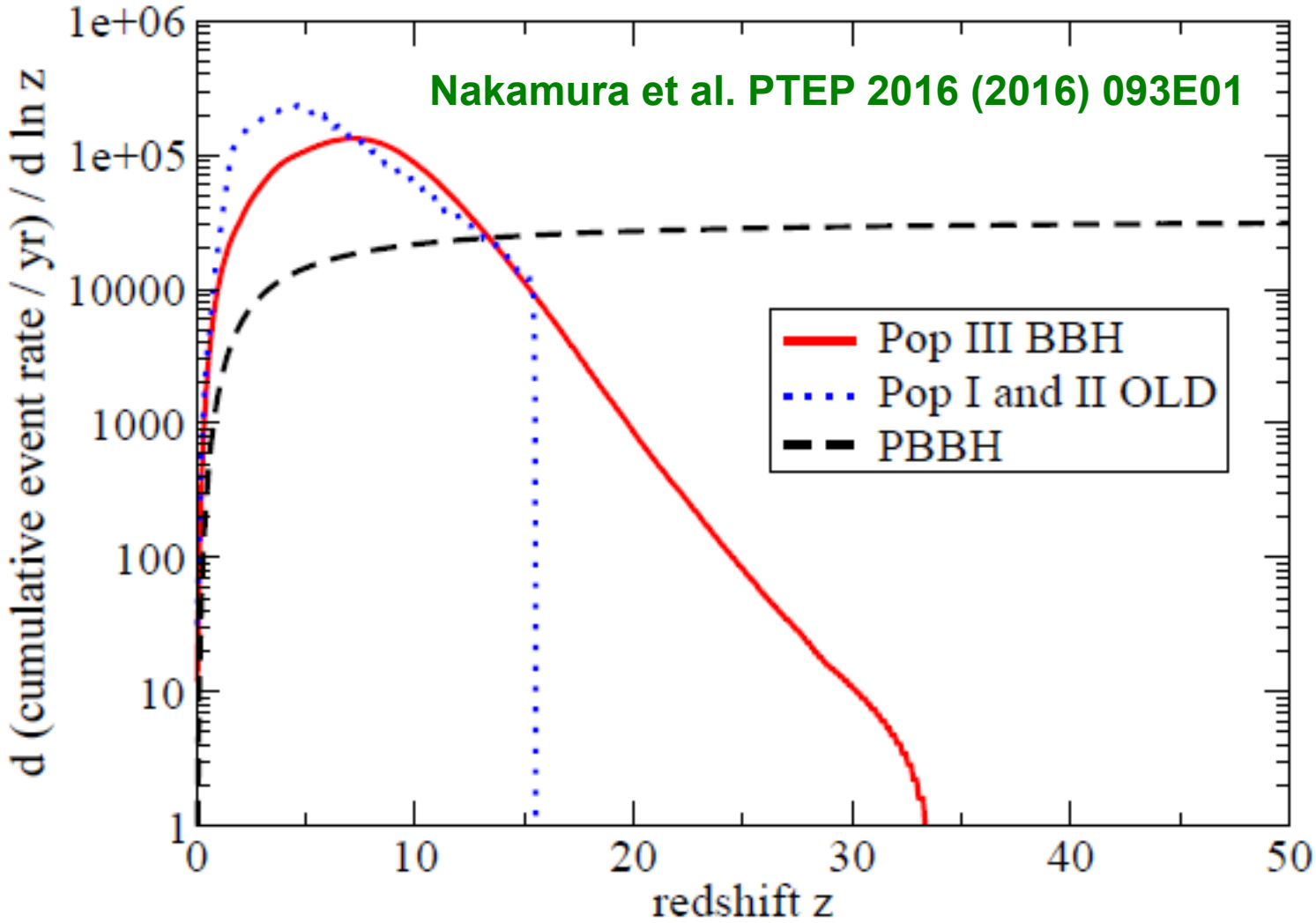


f = fraction of PBH in dark matter

tightest constraint at $M \sim 10 M_\odot$

(cf. Ali-Haïmoud et al., 1709.06576)

testing PBH hypothesis



testing PBH hypothesis 2

Kocsis, Suyama, Tanaka, Yokoyama, arXiv:1709.09007

BBH Merger Rate at time t:

mass function

$$\mathcal{R}(m_1, m_2, t) = \frac{n_{\rm BH}}{2} f(m_1) f(m_2) P_{\rm intr}(m_1, m_2, t)$$

intrinsic probability

$$P_{\rm intr}(m_1, m_2, t) \propto g(m_1) g(m_2) m_t^{\alpha} : \quad m_t = m_1 + m_2$$

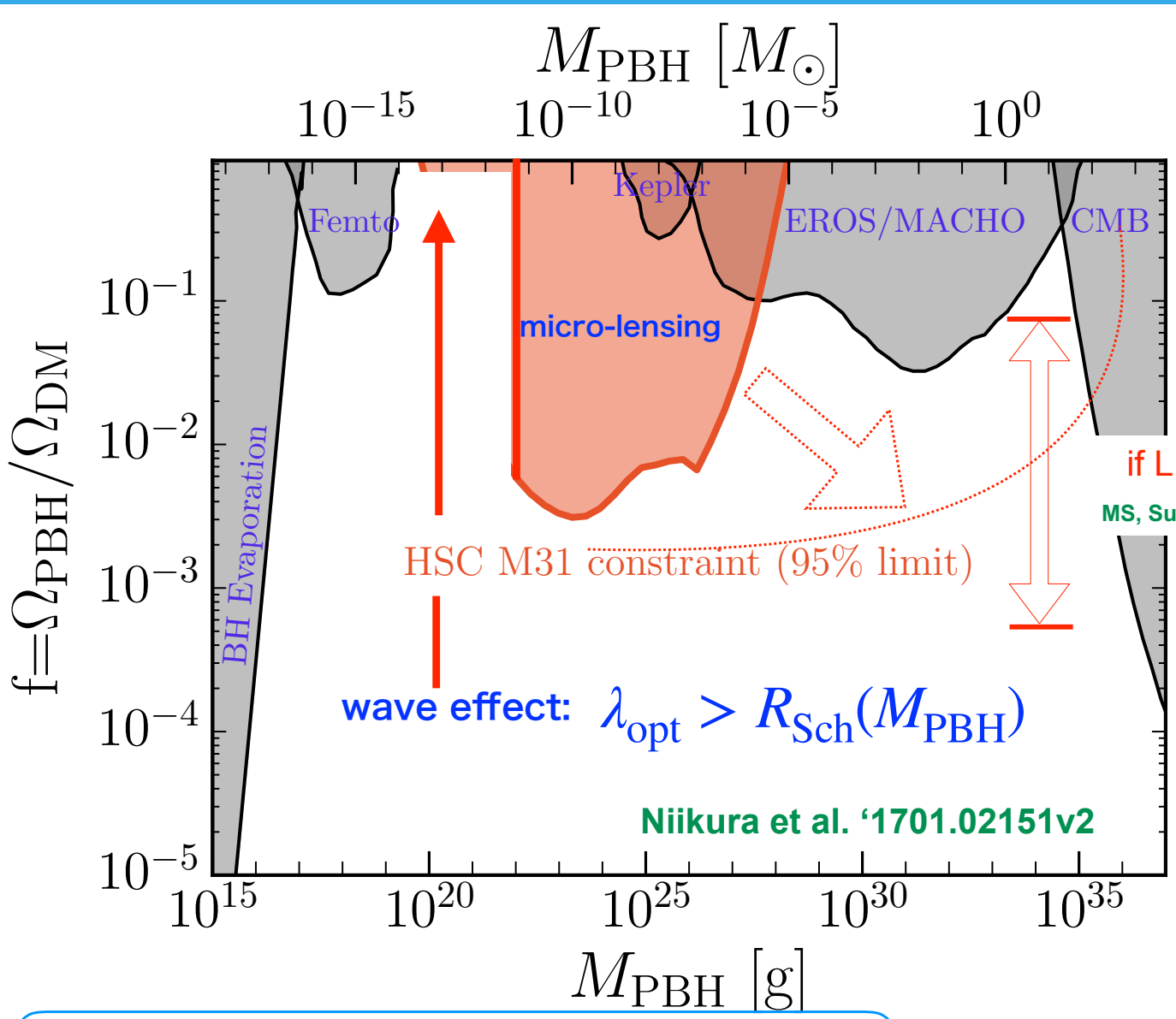
$$\Leftrightarrow \quad \alpha(m_1, m_2, t) \equiv -m_t^2 \frac{\partial^2}{\partial m_1 \partial m_2} \ln \mathcal{R}(m_1, m_2, t)$$

- PBH binary scenario $\quad \frac{36}{37} < \alpha < \frac{22}{21}$
- Dynamical formation in dense stellar systems $\quad \alpha \approx 4$

clearly distinguishable!

O'Leary et al (2016)

PBH constraints: recent update



for ~5 yrs obs

if LIGO BHs=PBHs

MS, Suyama, Tanaka, Yokoyama '16

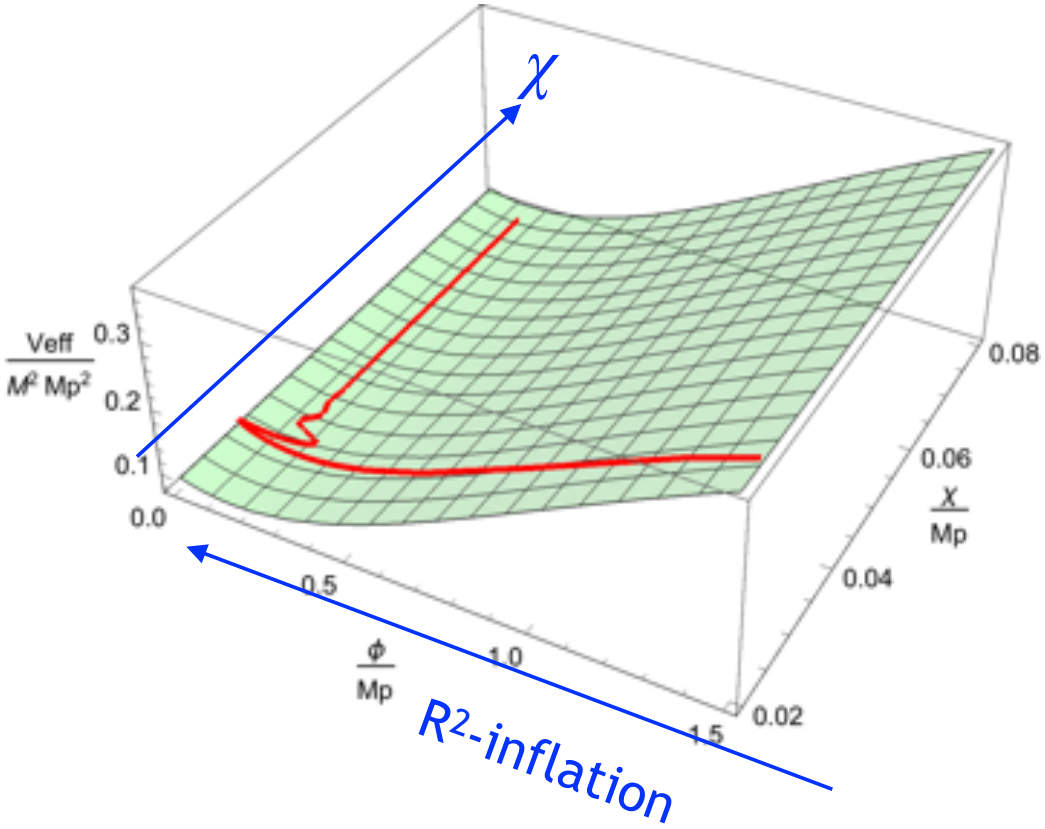
window only at $M_{\rm PBH} \approx 10^{20} - 10^{23}$ g ⟷ $T_{\text{re-entry}} \sim 10^2$ -10^3 TeV

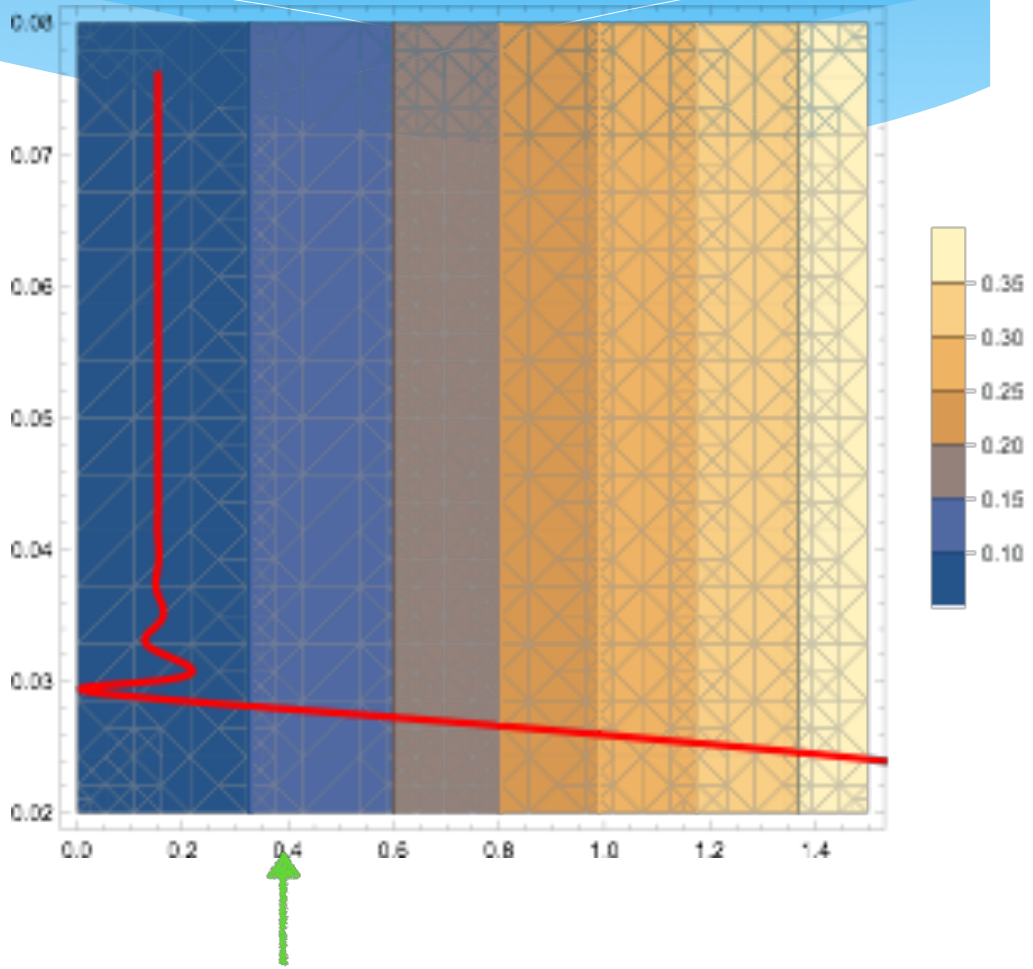
PBHs = CDM?

monocromatic PBH production

Pi, Zhang, Huang & MS '18

$$\mathscr{L} = R + \frac{R^2}{6M^2} - \frac{1}{2}(\partial\chi)^2 - V(\chi)$$



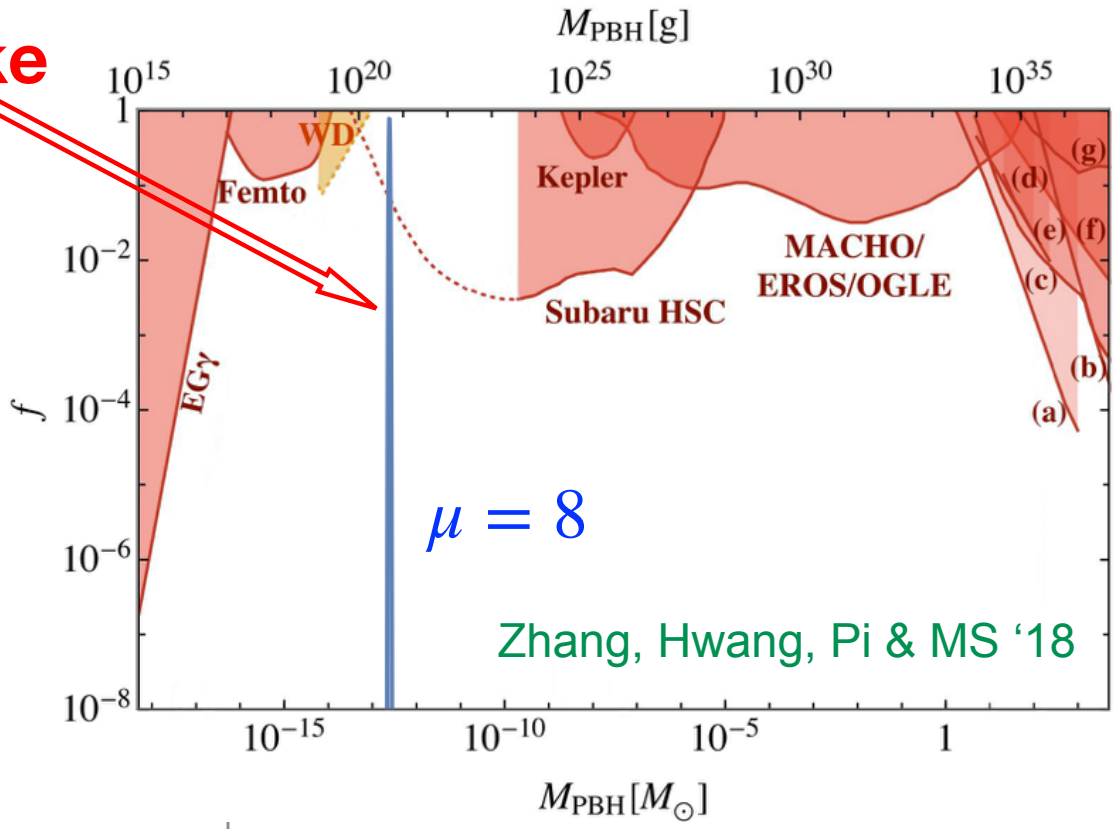


End of the 1st stage of inflation

sharp peak in P(k) → spike in f

$$f \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}} \propto \exp\left[-\frac{1}{\mathscr{P}(k)}\right]$$

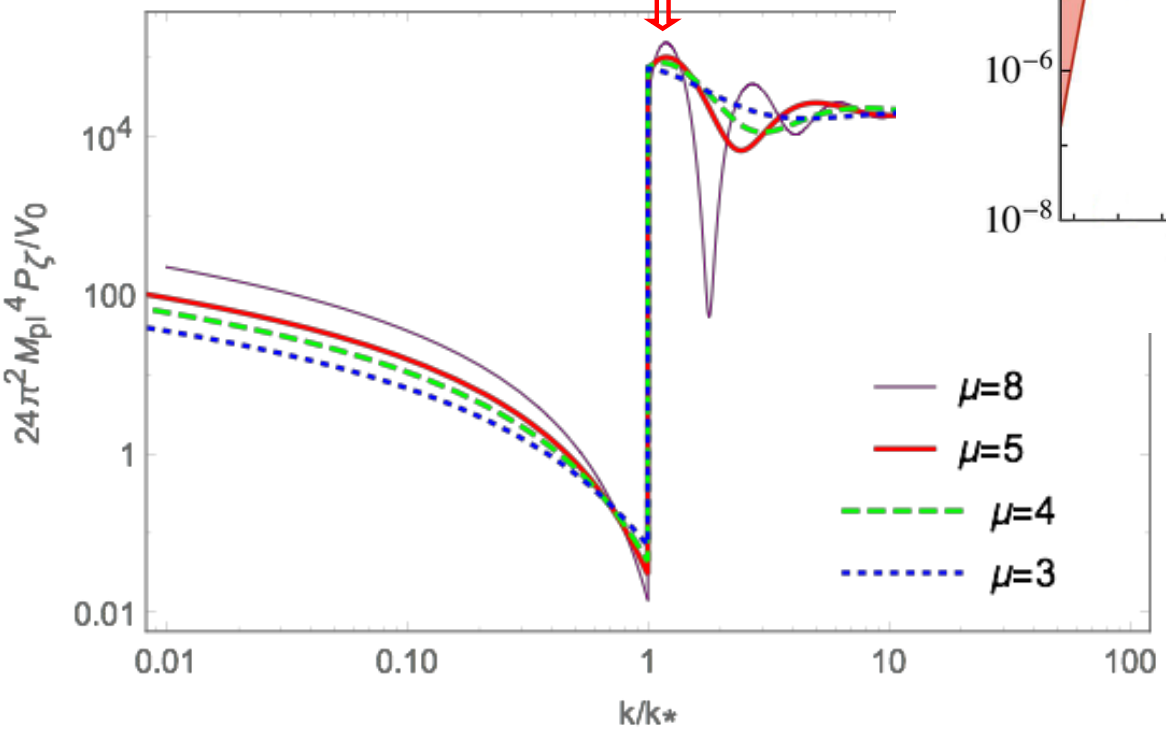
spike



$\mu = 8$

Zhang, Hwang, Pi & MS '18

sharp peak



$$\mu^2 \approx \frac{H_{\rm 2nd}^2}{H_{\rm 1st}^2}$$

2nd order GWs

Saito & Yokoyama '09, Alabidi et al. '13, …

- non-negligible PBH formation means $\mathcal{P}_S(k) \gtrsim 10^{-2.5}$

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - a^{-2}\Delta h_{ij} = S_{ij}$$

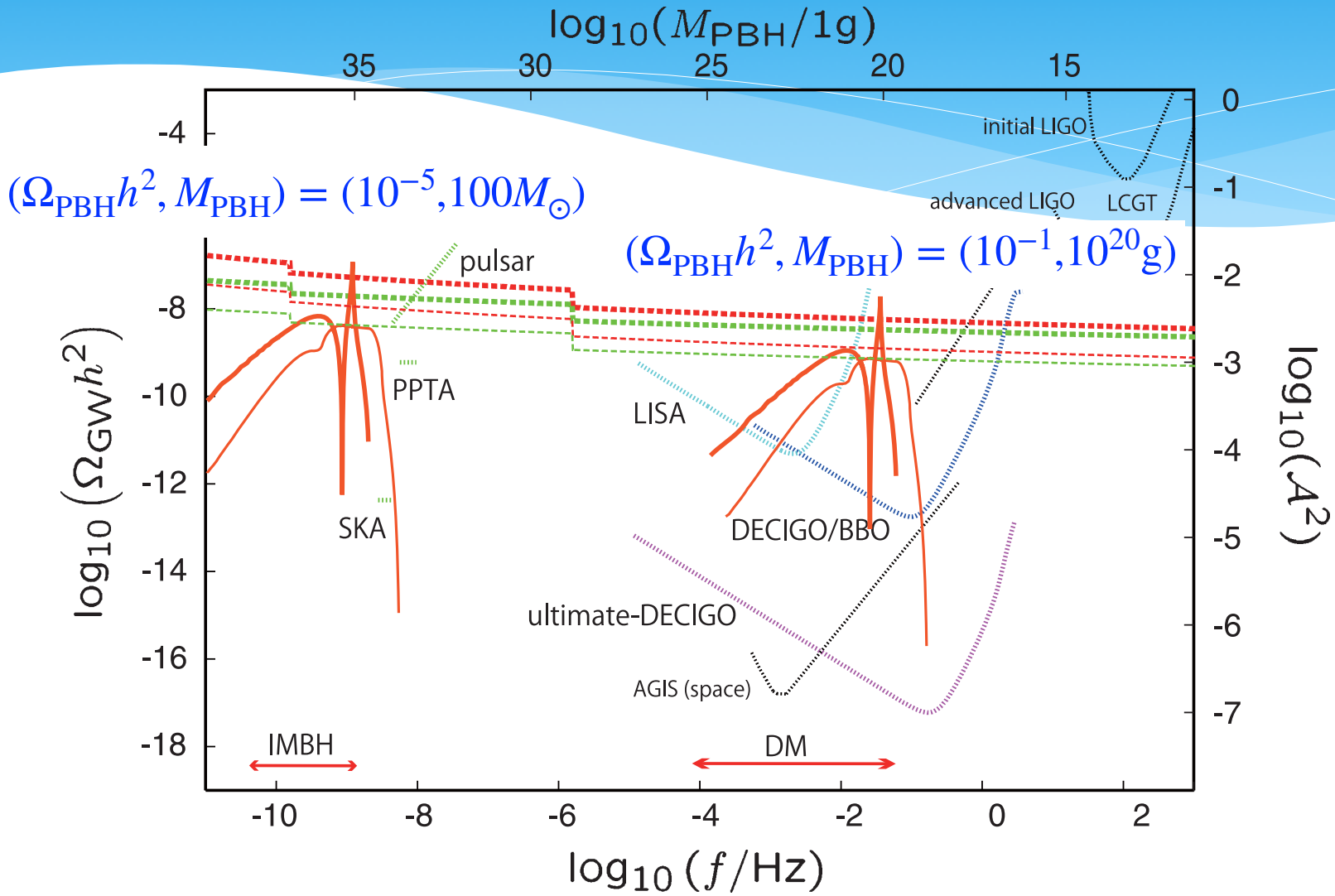
$$S_{ij} = \frac{1}{a^2}\partial_i \mathcal{R}_c \partial_j \mathcal{R}_c + \cdots \sim \frac{k^2}{a^2}\mathcal{P}_S(k)$$

- GWs are produced with amplitude:

$$h_{ij} \sim \frac{k^2}{a^2 H^2}\mathcal{P}_S(k) \sim \mathcal{P}_S(k) \quad \Rightarrow \quad \mathcal{P}_{GW}(k) \sim \left(\mathcal{P}_S(k)\right)^2$$

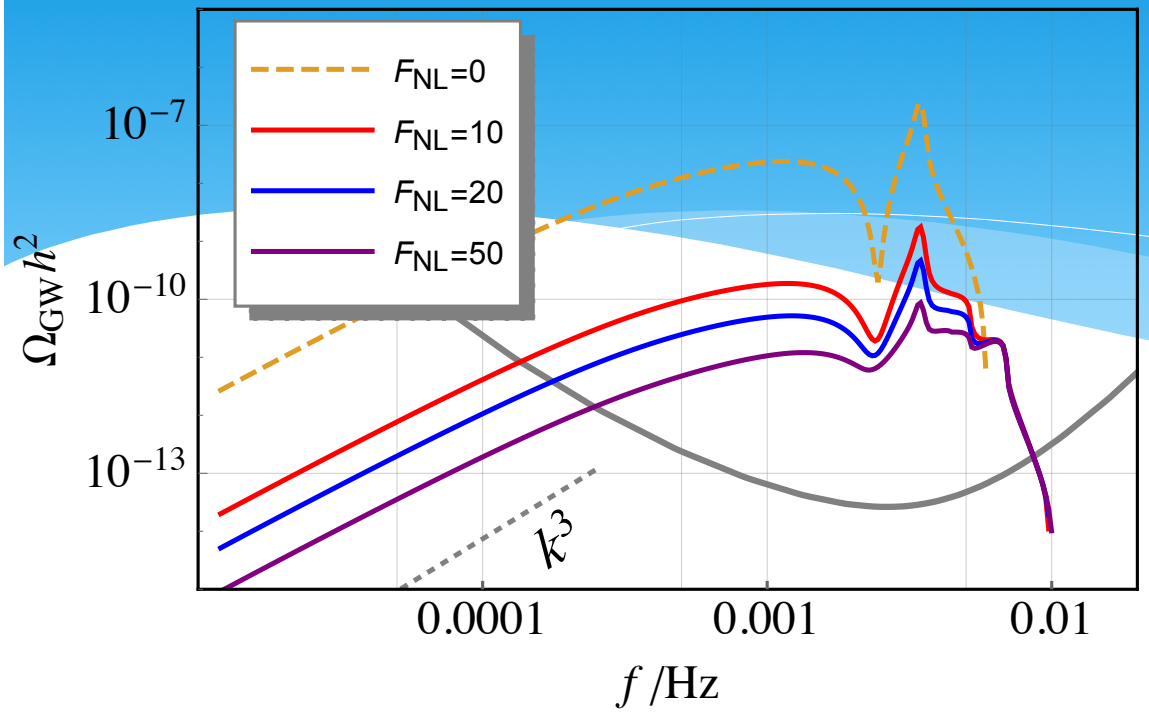
2nd order GWs could dominate GW background at $f > 10^{-10}$ Hz ($k > 10^4$ Mpc^{-1})

GWs test PBH scenarios!



Saito & Yokoyama,arXiv:0912.5317

Non-Gaussianity Effect?



RG Cai, S Pi & MS, arXiv:1810.11000

$$\mathscr{R}(x) = \mathscr{R}_g(x) + F_{\rm NL}\left[\mathscr{R}_g^2(x) - \langle \mathscr{R}_g^2(x)\rangle\right]$$

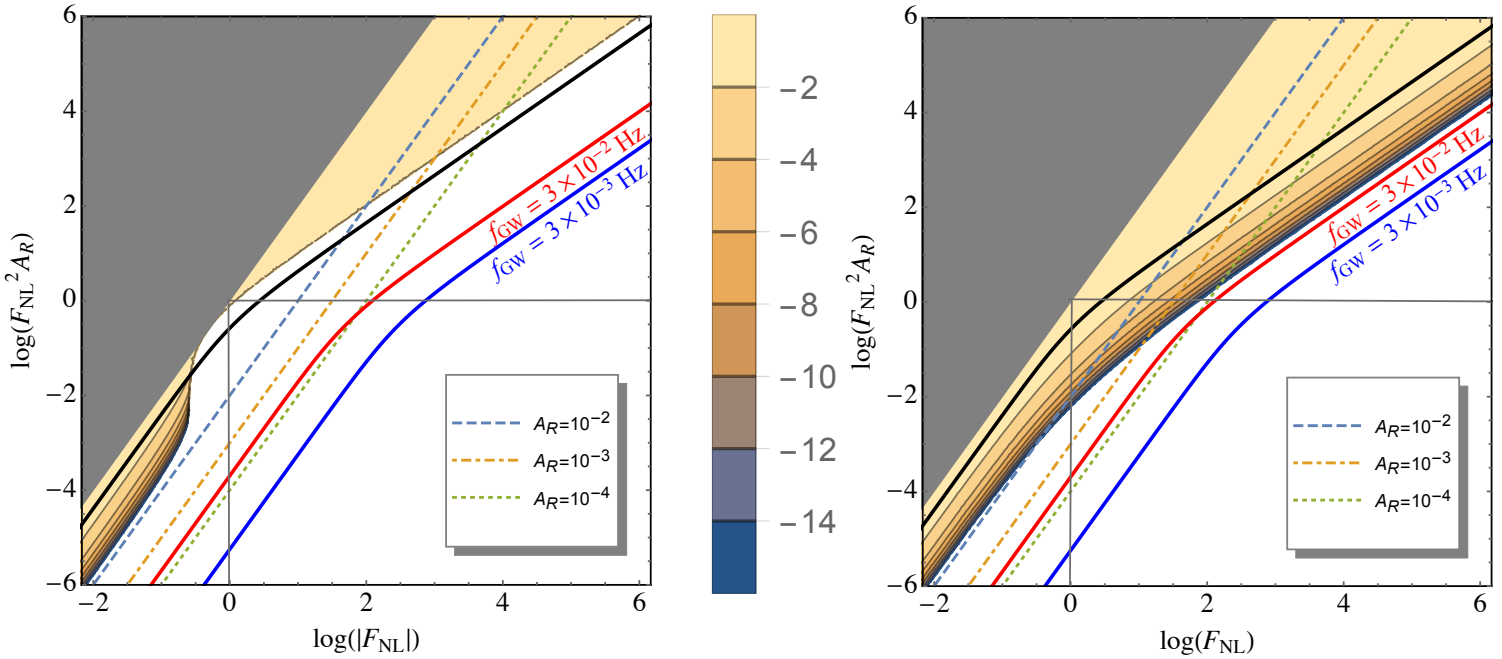
$$M_{\rm PBH} = 10^{22}\,{\rm g}$$

PBH constraints:

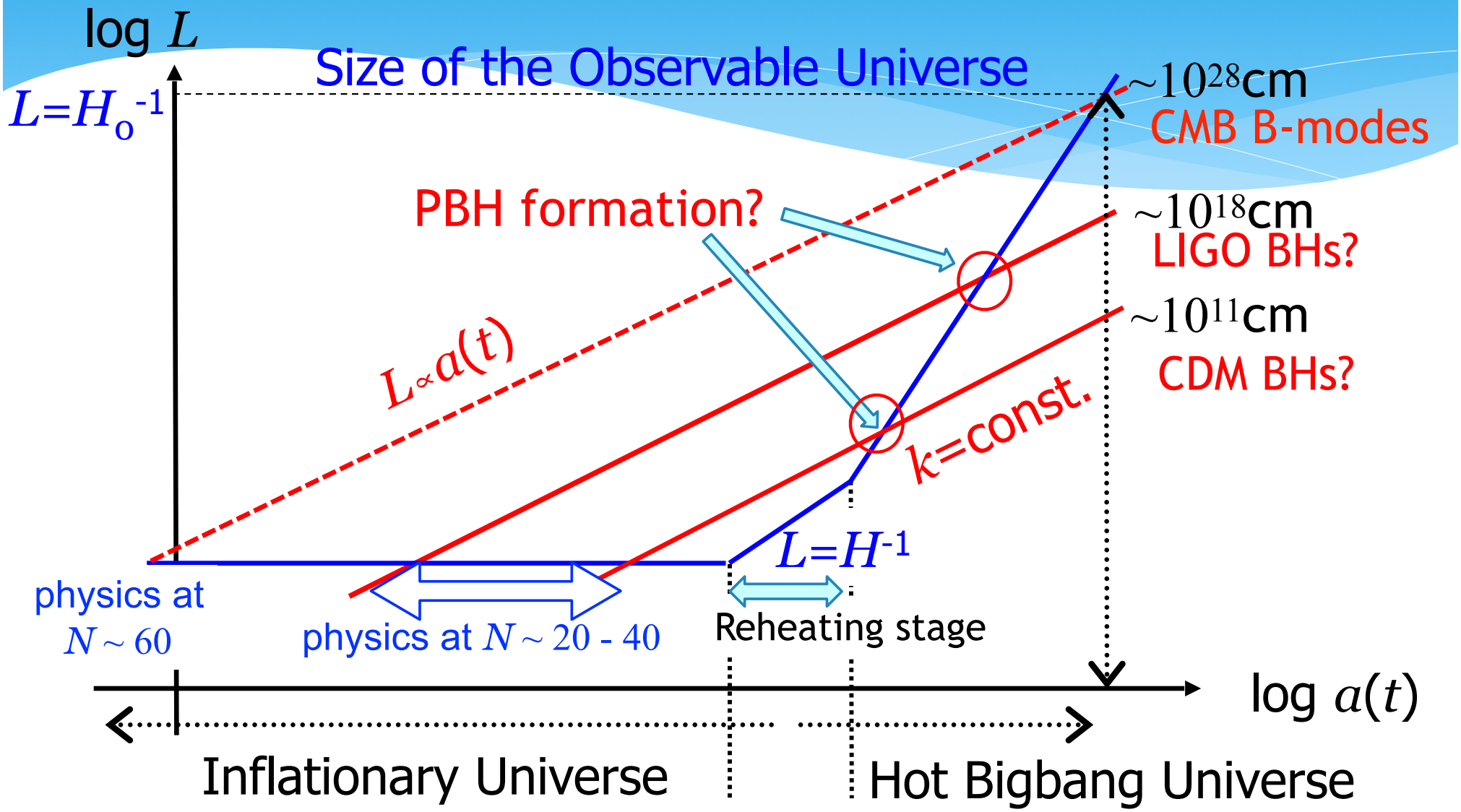
If PBHs=CDM

LISA must detect

induced GWs!



probing inflation by GW astronomy



Summary

* Inflation has become the standard model of the Universe.
  further tests are needed to confirm inflation.

* Inflation can produce large curvature perturbation on small scales.
  PBHs are virtually the only probe on very small scales.

* LIGO BHs may be primordial.
  future GW detectors(+G lensing) will prove/disprove the scenario.

* CDM can be dominated by PBHs of $M\sim10^{20}g$.
  secondary GWs may be detected by future GW detectors.

* Multi-frequency GW astronomy/astrophysics is arriving!

GWs will be an essential tool for proving/ falsifying PBH scenarios