KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

DSU18
LAPTh, Annecy
29 June, 2018

Primordial Black holes

and
gravitational waves

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LeCosPA, National Taiwan University

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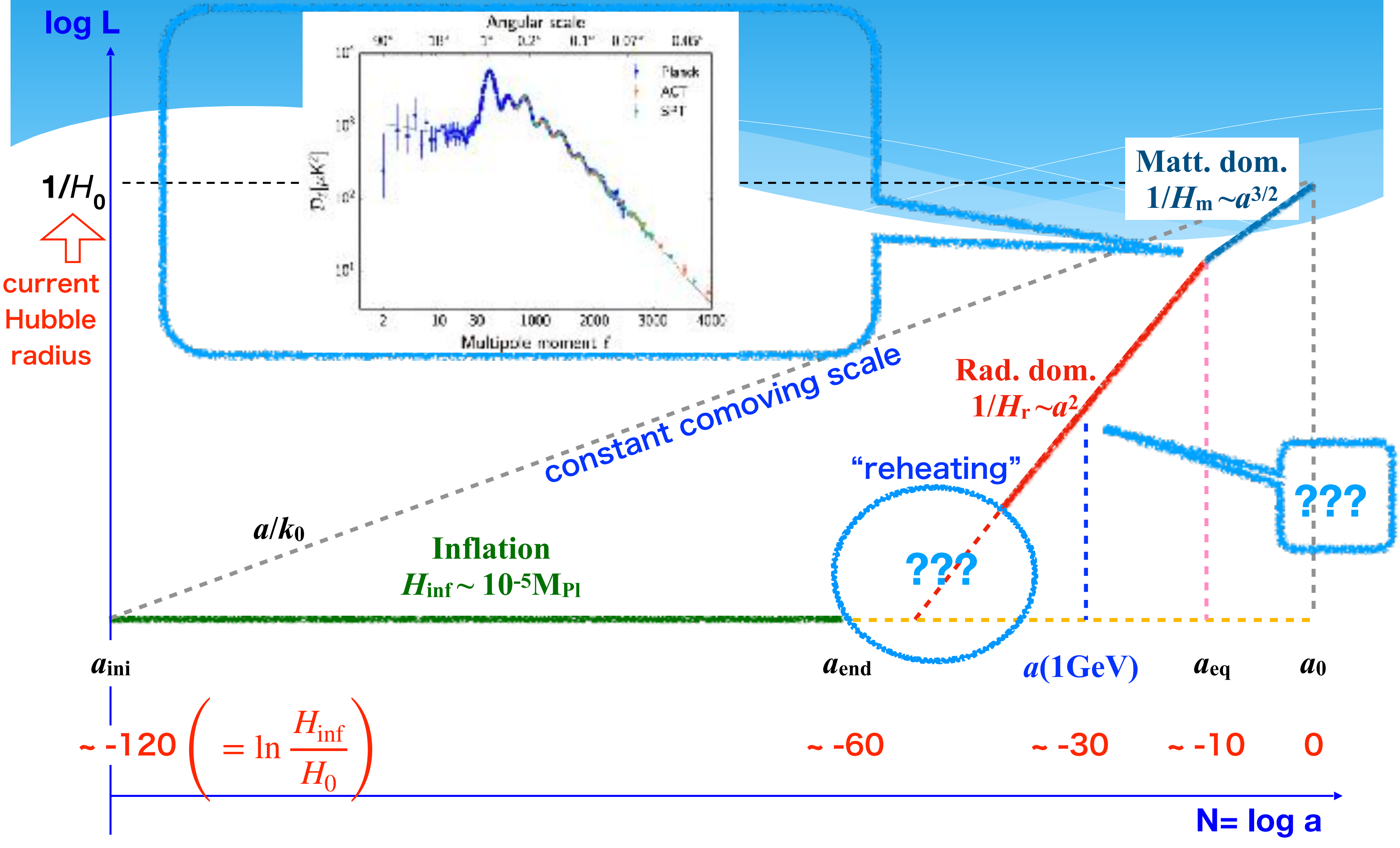
LeCosPA

Inflation & PBH formation

cosmic spacetime diagram



curvature perturbation from inflation

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

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

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

(fluctuations become "classical" on superhorizon scales)

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

··· almost scale-invariant

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

- curvature perturbation on comoving slices

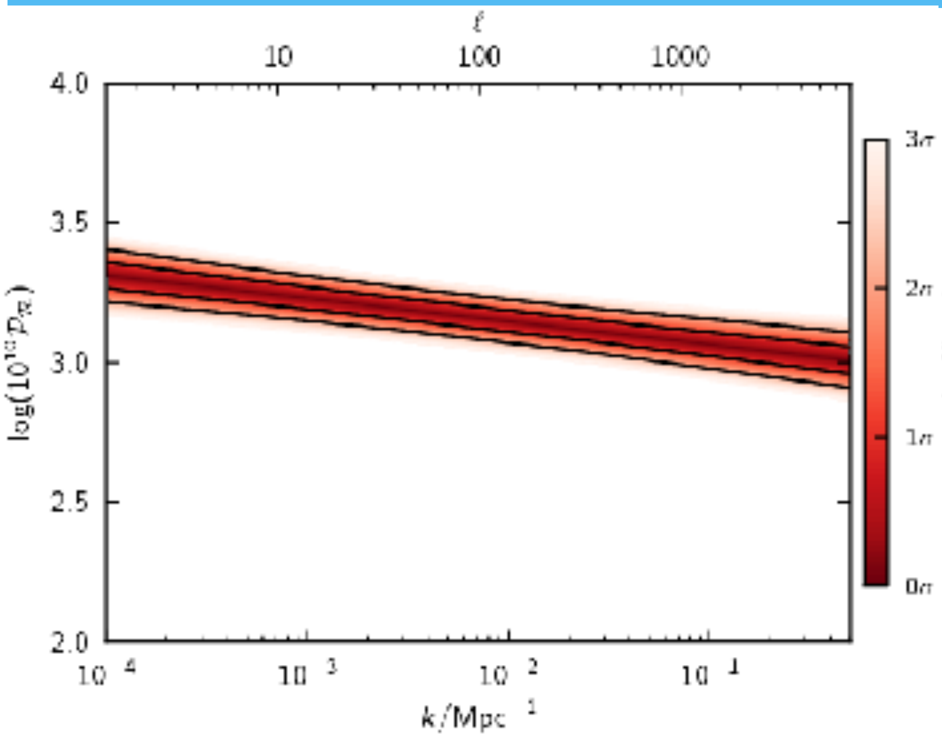
$$\mathscr{R}_c = -\frac{H}{\dot{\phi}} \delta\phi$$

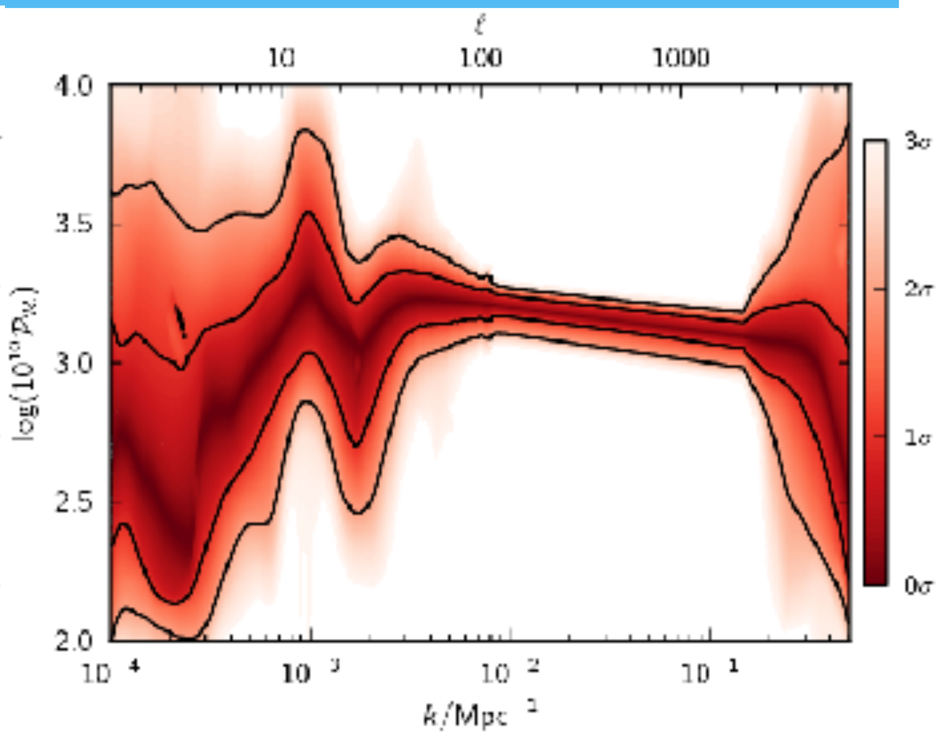
··· conserved on superhorizon scale for single-field slow-roll models

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

observational constraint on inflation

Planck 2015 results XX





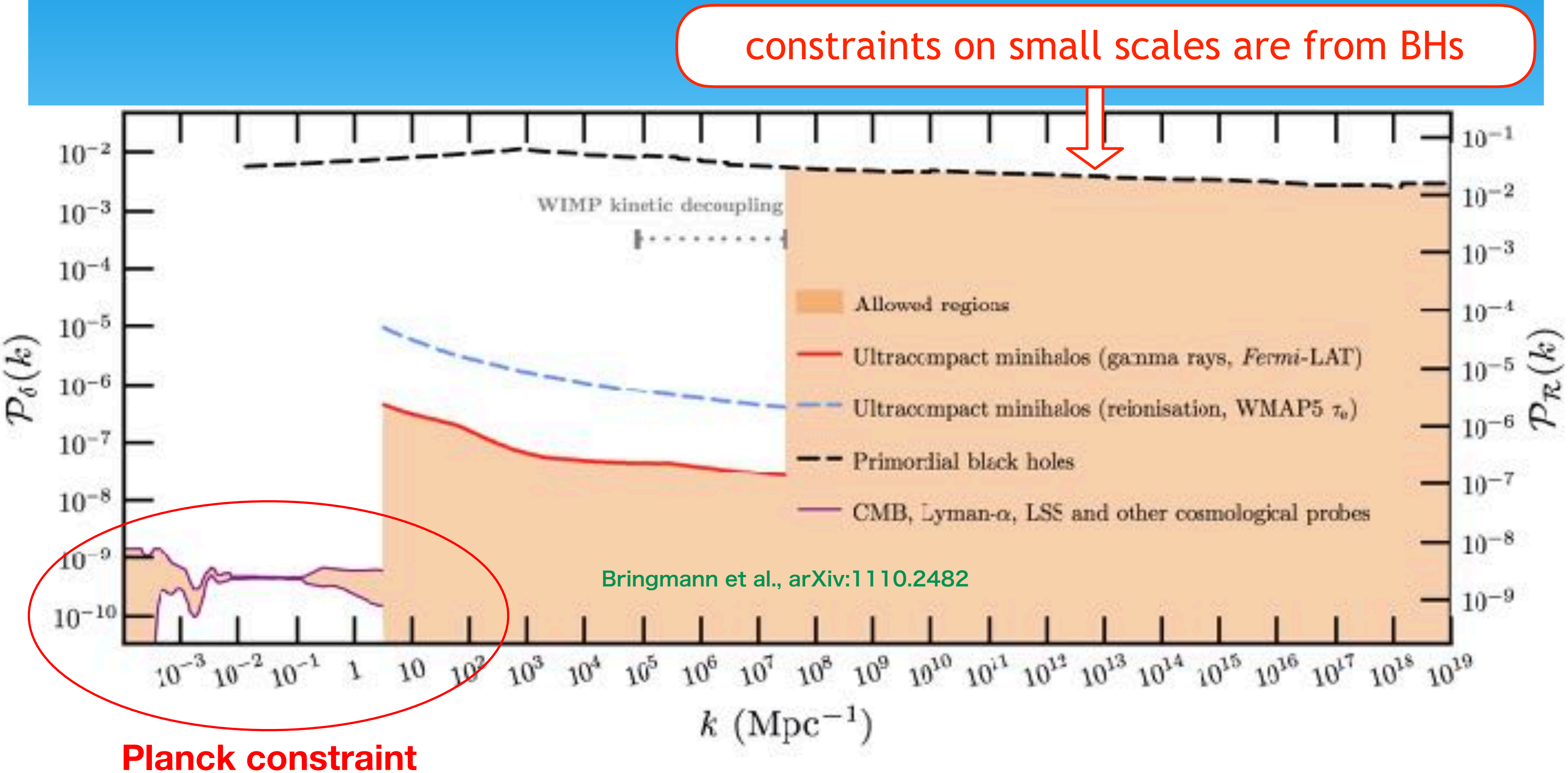
power-law

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

piece-wise continuous (9 segments)

$n_s \approx 0.968$ ⋯ almost scale-invariant

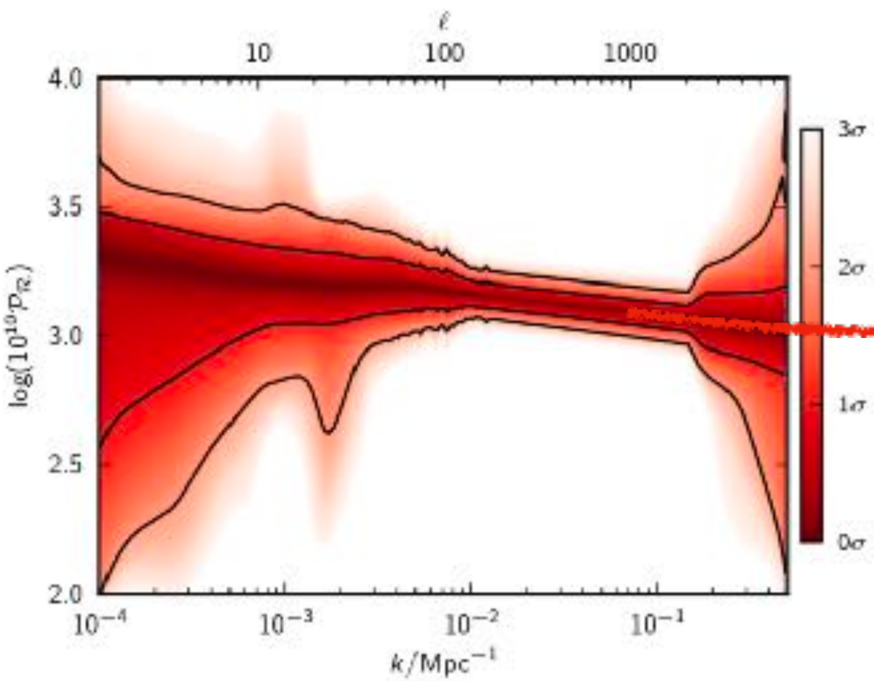
observational constraint on inflation



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

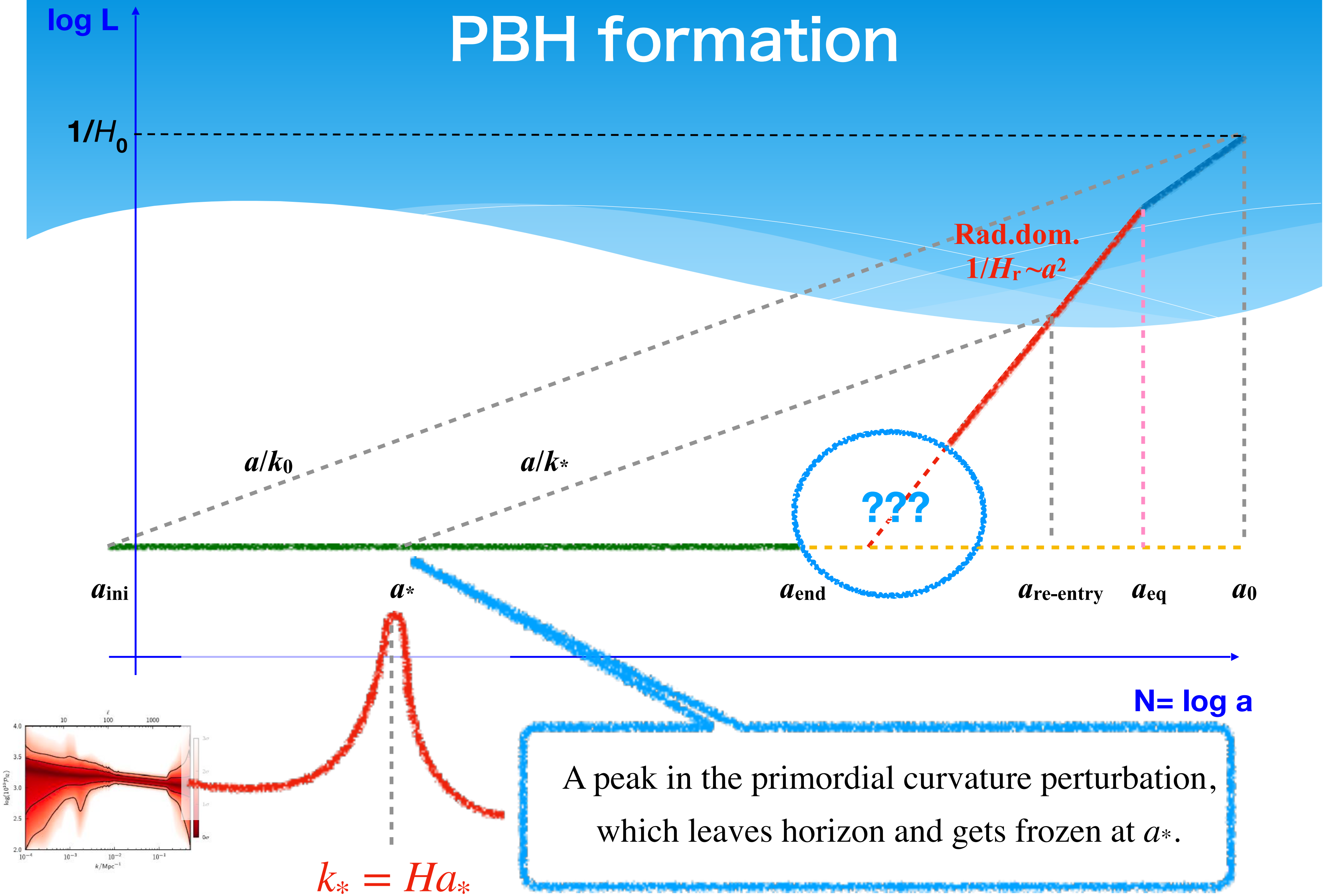
?

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

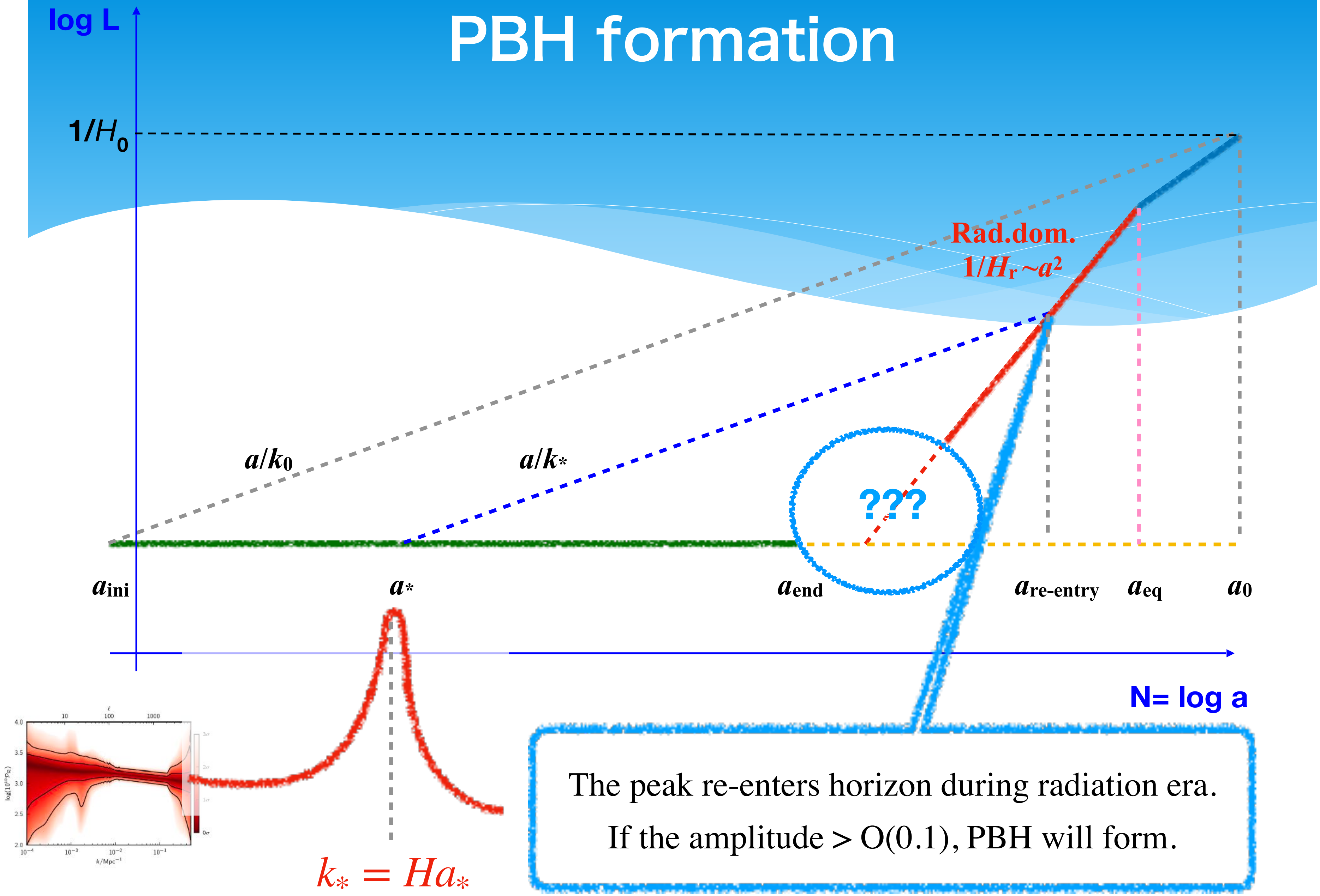


No resolution to say anything precise about higher *k*.

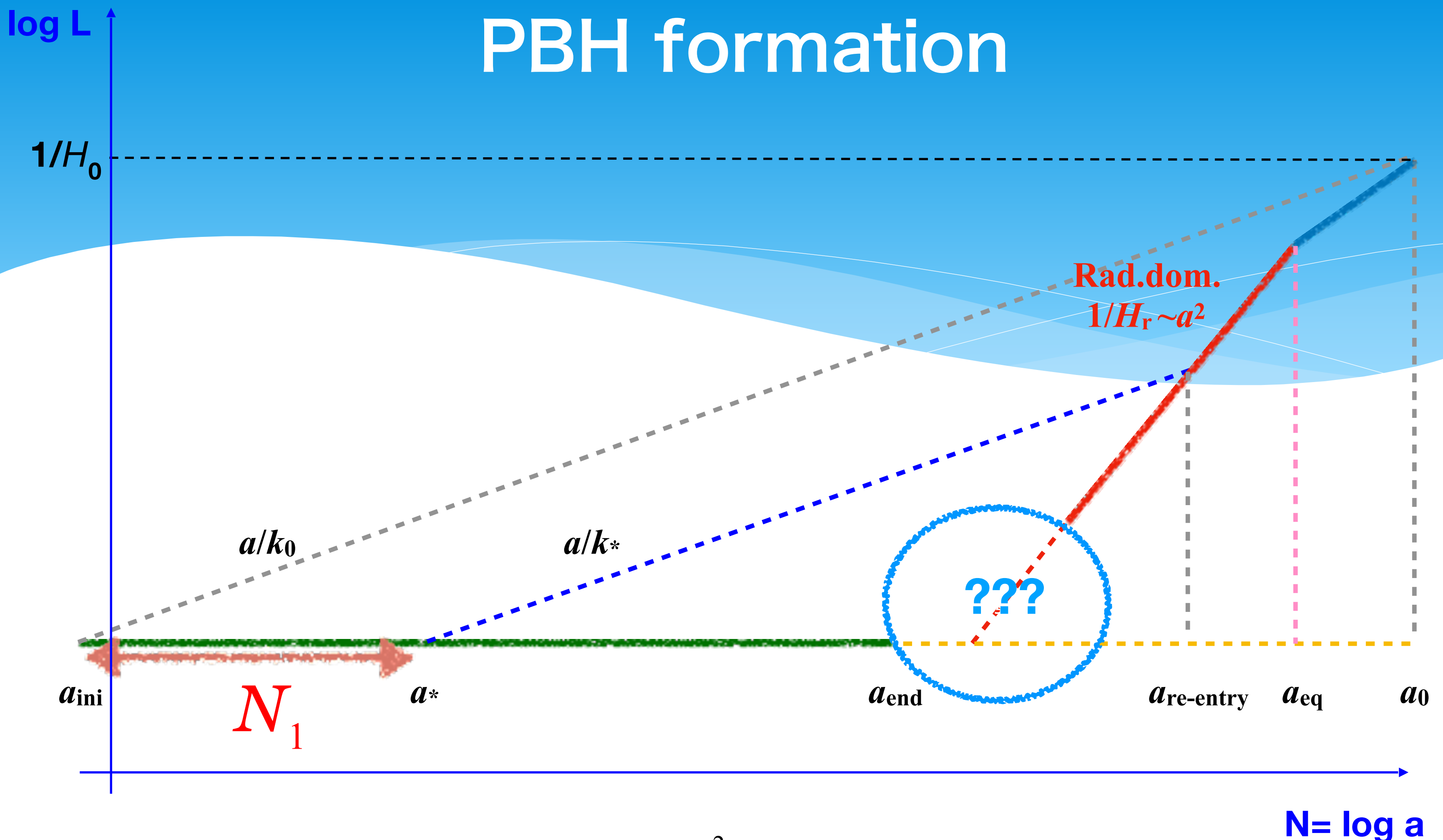
PBH formation



PBH formation



PBH formation



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

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

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.

- ➢ ….

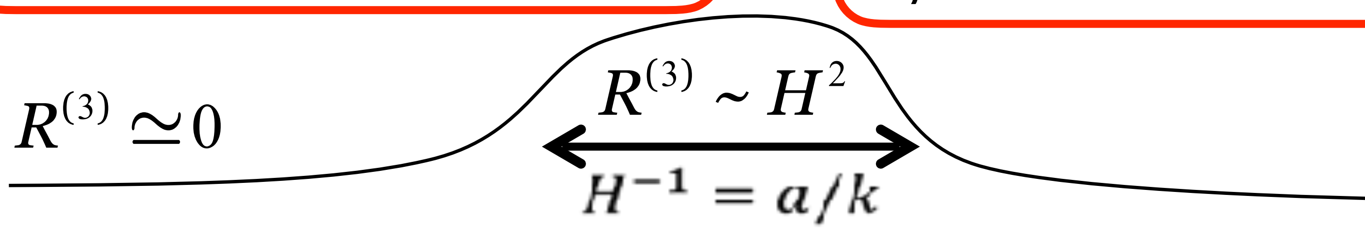
Curvature perturbation to PBH

➢ gradient expansion/separate universe approach

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

Hamiltonian constraint (Friedmann eq.)

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



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

Young, Byrnes & MS '14

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

➢Spins of PBHs are expected to be very small

examples

hybrid-type inflation

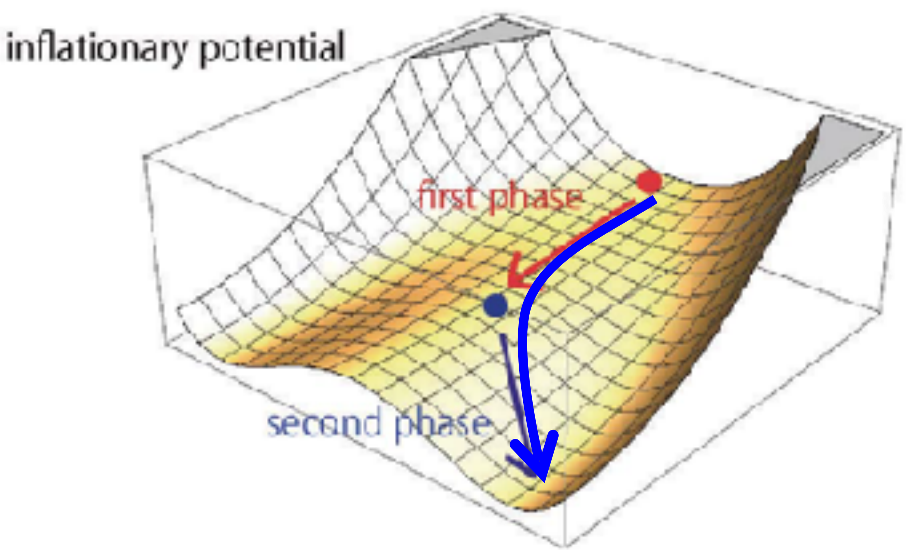
Garcia-Bellido, Linde & Wands ‘96, …

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

non-Gauss may become large

Abolhasani, Firouzjahi & MS ’11,..

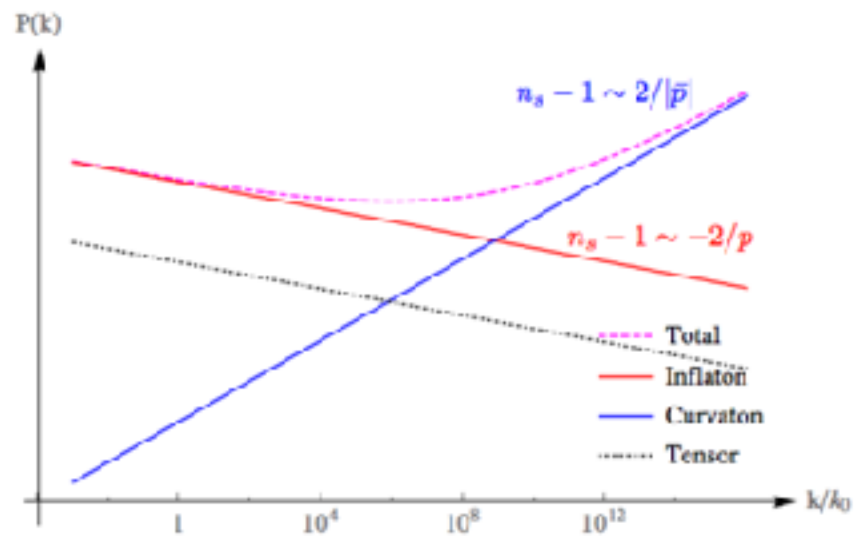
Pattison et al. 1707.00537



non-minimal curvaton

Domenech & MS ‘16

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



Accretion to PBH?

➢ Bondi accretion

$$\dot{M} = \lambda \cdot 4\pi r_B^2 \rho c_s : \quad c_s = \sqrt{P/\rho} \left(= 1/\sqrt{3}\right), \quad r_B = \frac{GM}{c_s^2}, \quad \lambda \lesssim O(1)$$

- accretion rate/Hubble time

$$\Rightarrow \frac{\dot{M}}{HM} = \lambda \frac{3}{4} \frac{H}{H_M} : \quad M = \frac{4\pi\rho_M}{3}\left(c_s H_M^{-1}\right)^3 = \frac{c_s^3}{2GH_M}, \quad \frac{H}{H_M} = \left(\frac{a_M}{a}\right)^2$$

horizon size at the time of PBH formation

$$\Rightarrow \int_{a_M}^{\infty} \frac{\dot{M}}{H} \frac{da}{a} \simeq \lambda \frac{3}{8} M$$

PBH mass can increase by a factor of 1.5 at most

Mass increase can be ignored, given other ambiguities

Effect on CMB?

accretion can lead to radiative emission

- Eddington luminosity: max luminosity from accretion

$$L_{\rm edd} = \frac{4\pi G M m_p c}{\sigma_T};$$

m_p = proton mass

σ_T = Thomson cross section

$$L = \varepsilon L_{\rm edd}; \quad \varepsilon \leq 1$$

… luminosity from PBH

- energy output/Hubble time

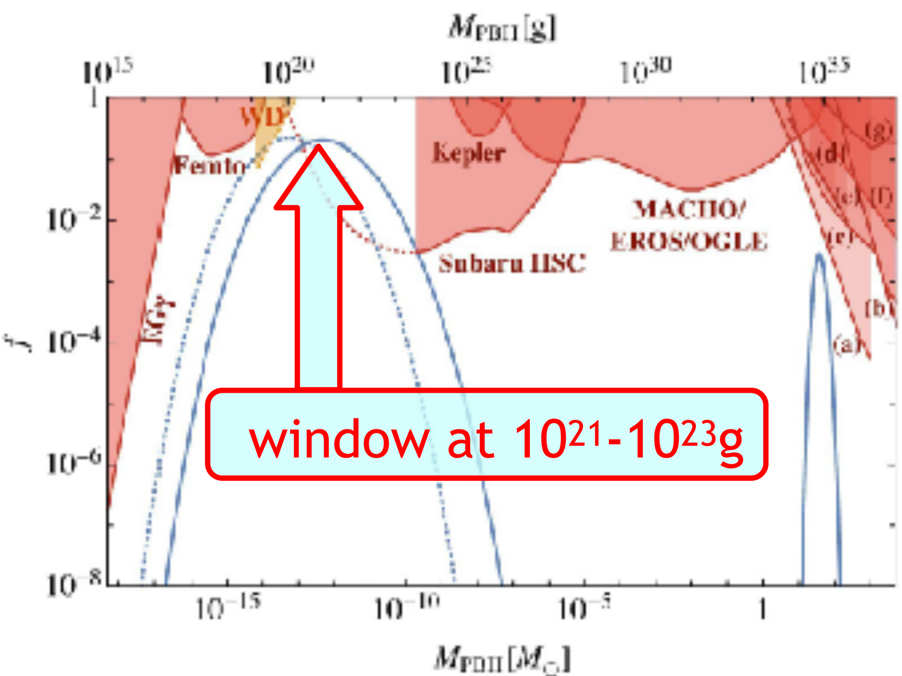
$$\frac{\dot{\rho}_R}{H\rho_R} = \varepsilon \frac{n_{PBH} L_{\rm edd}}{H\rho_R} = \varepsilon \frac{\rho_{PBH}}{\rho_R} \frac{4\pi G m_p}{\sigma_T H} = \varepsilon f_{PBH} \left(\frac{a}{a_{eq}}\right)^3 \frac{4\pi G m_p}{\sigma_T H_{eq}}$$

$$\simeq 10^{-4} \varepsilon f_{PBH} \left(\frac{a}{a_{eq}}\right)^3; \quad f_{PBH} = \frac{\Omega_{PBH}}{\Omega_{CDM}}$$

small, but may not be entirely negligible…

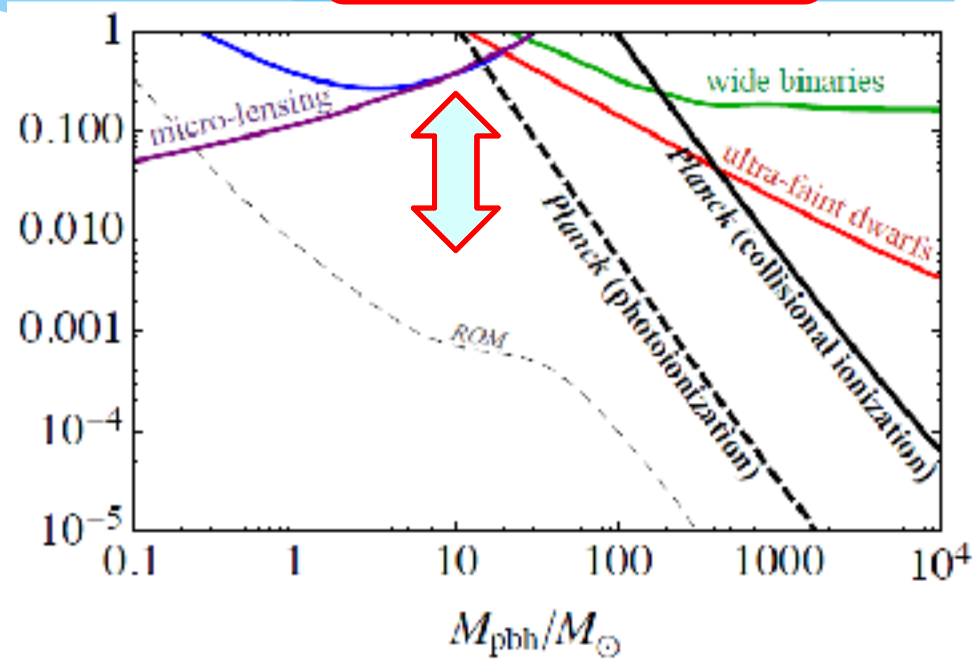
Constraints on PBHs

Can DM be PBHs?



Inomata et al., 1711.06129
(2-field model)

LIGO BBHs may occupy ~10% of DM



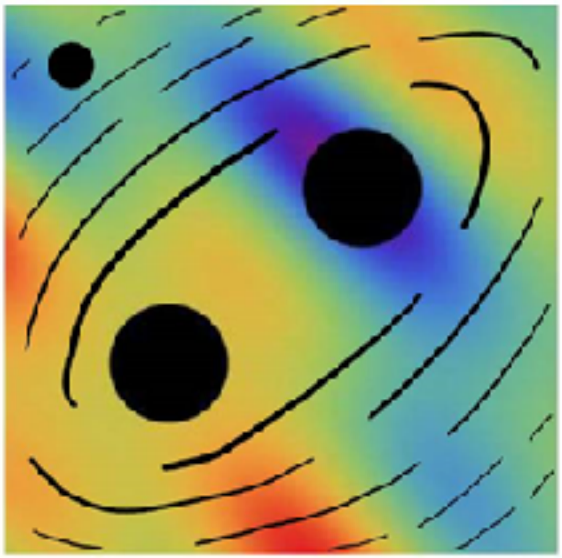
Ali-Haimoud & Kamionkowski, 1612.05644

Ricotti, Ostriker & Mack ('08) overestimated the accretion effect

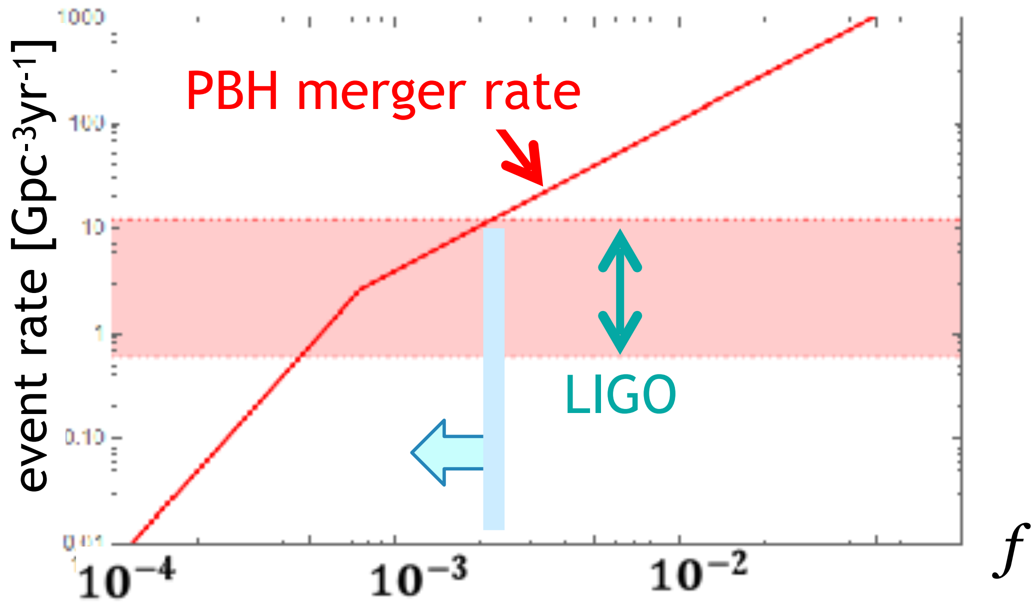
LIGO BHs = PBHs?

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

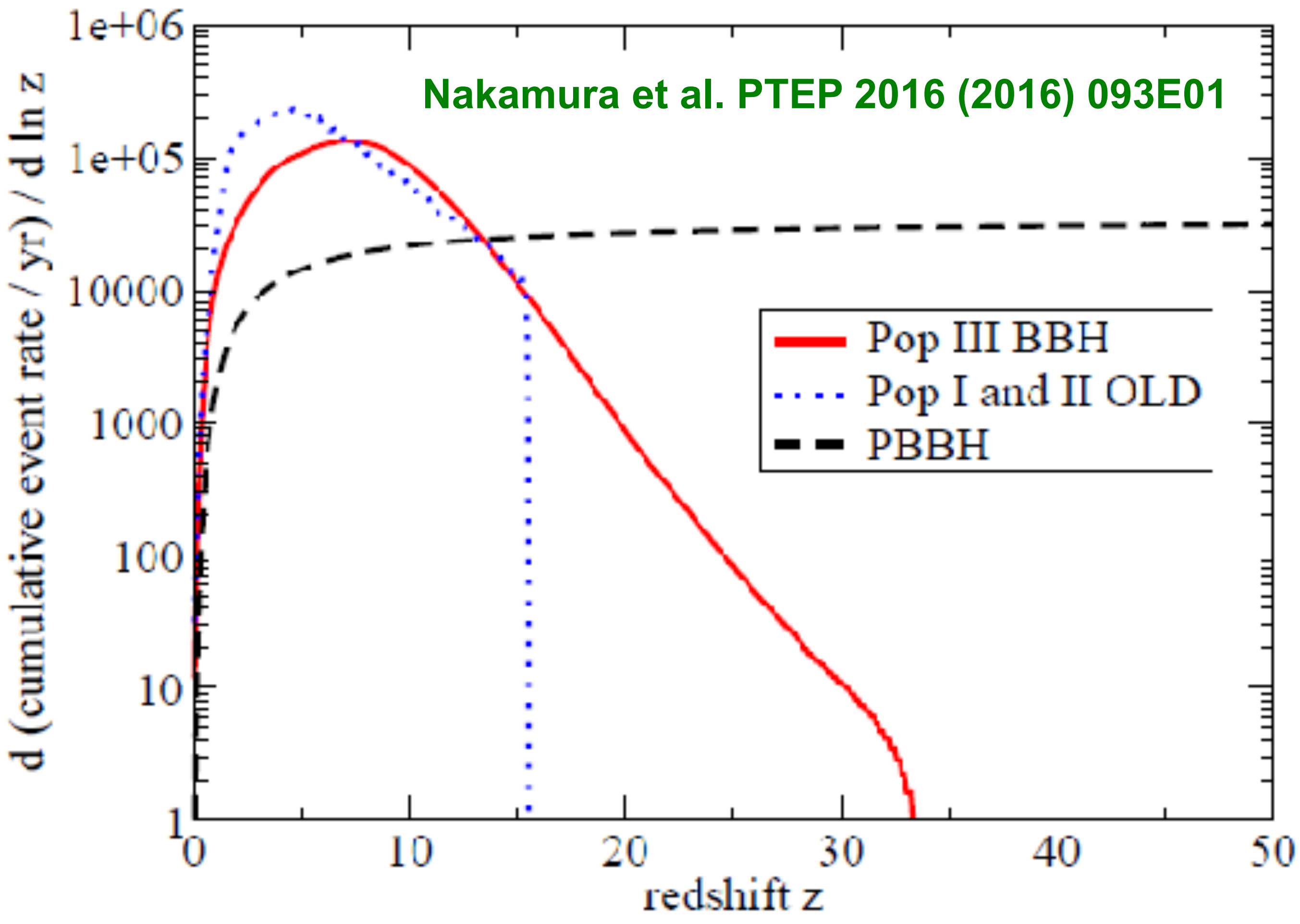


f = fraction of PBH in dark matter

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

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

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

- PBH binary scenario $\frac{36}{37} < \alpha < \frac{22}{21}$

$\Updownarrow$

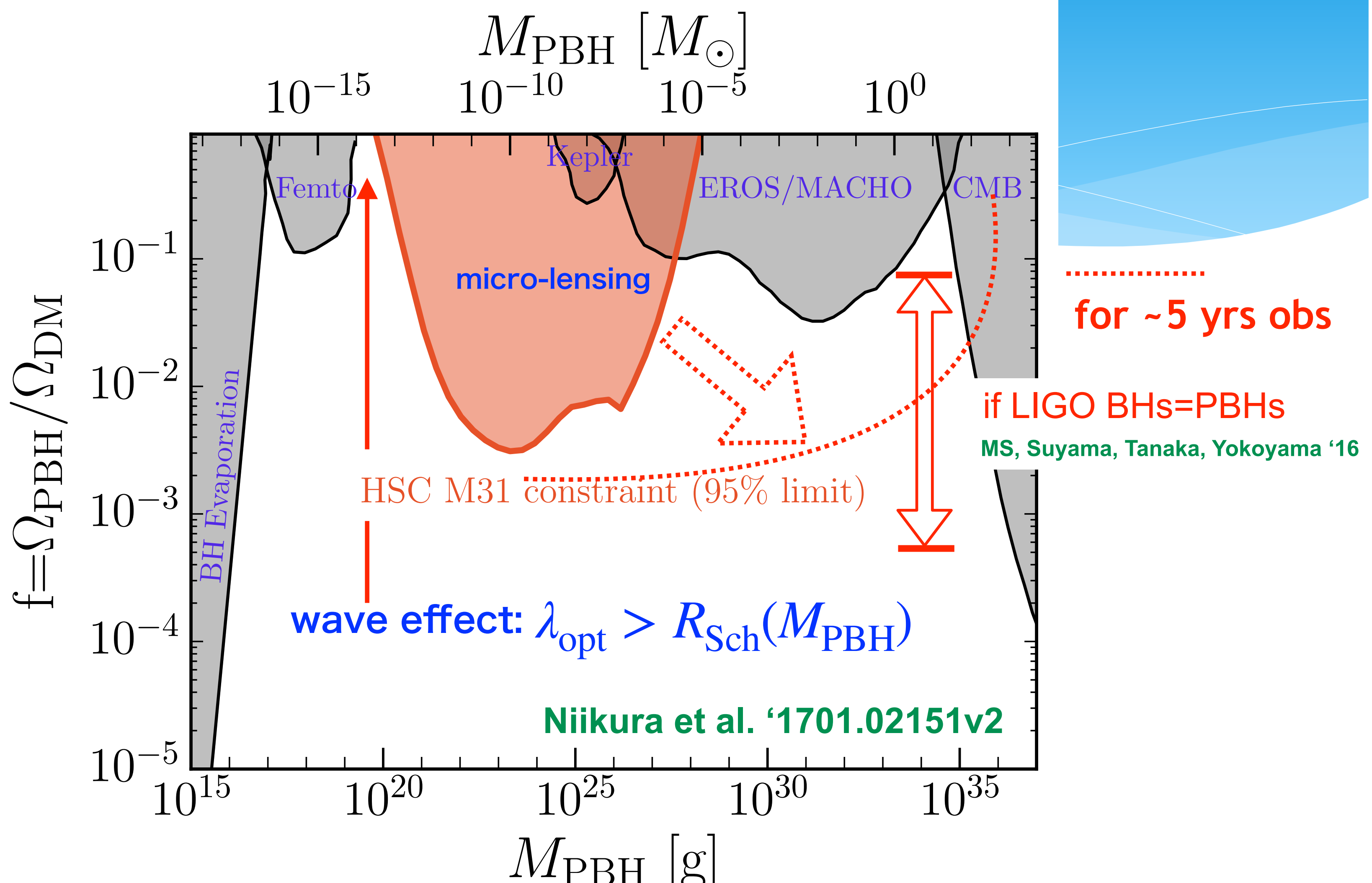
- Dynamical formation in dense stellar systems $\alpha \approx 4$

O'Leary et al (2016)

clearly distinguishable!

PBHs = CDM?

PBH constraints:revised

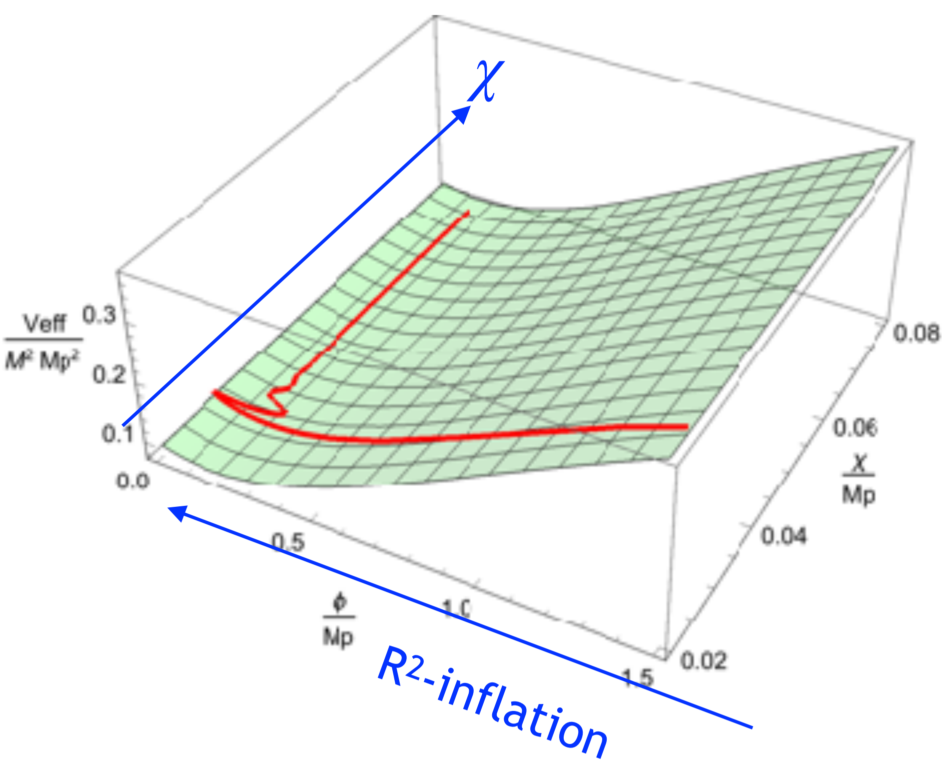


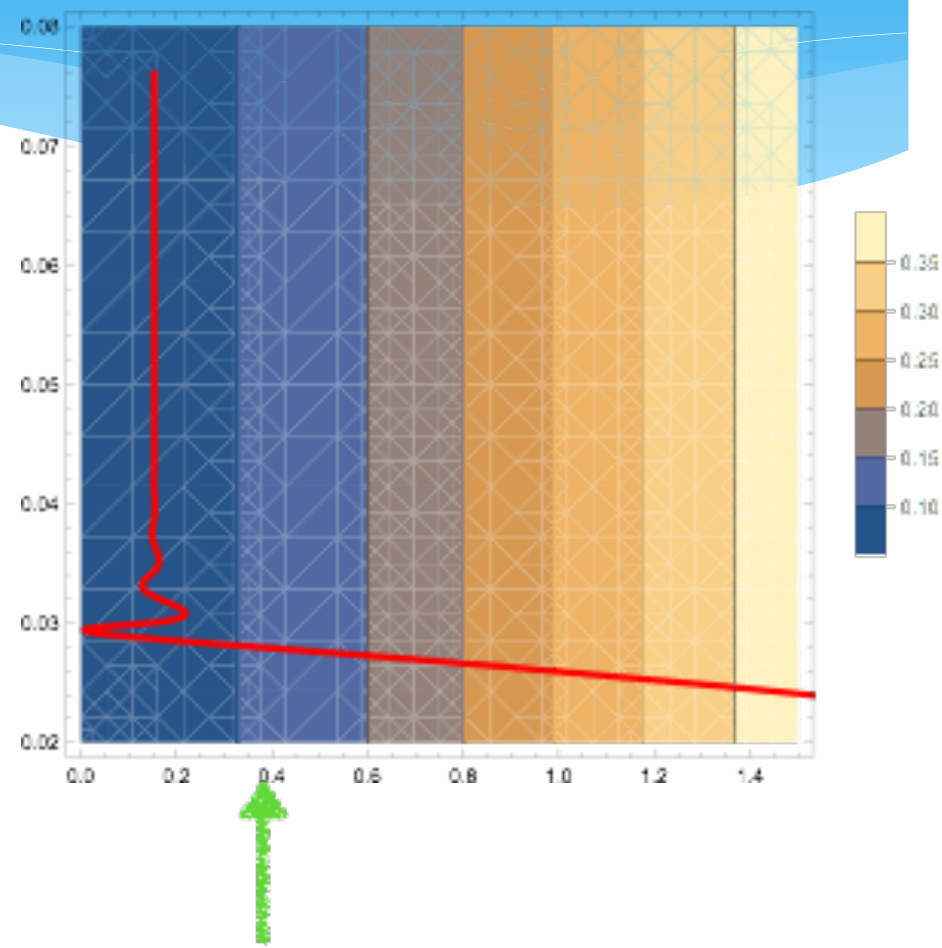
only narrow window at $M_{\rm PBH} \approx 10^{20}$ g ⟷ $T_{\text{re-entry}} \sim 10^3$ TeV

monocromatic PBH production

Zhang, Hwang, Pi & MS '18

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



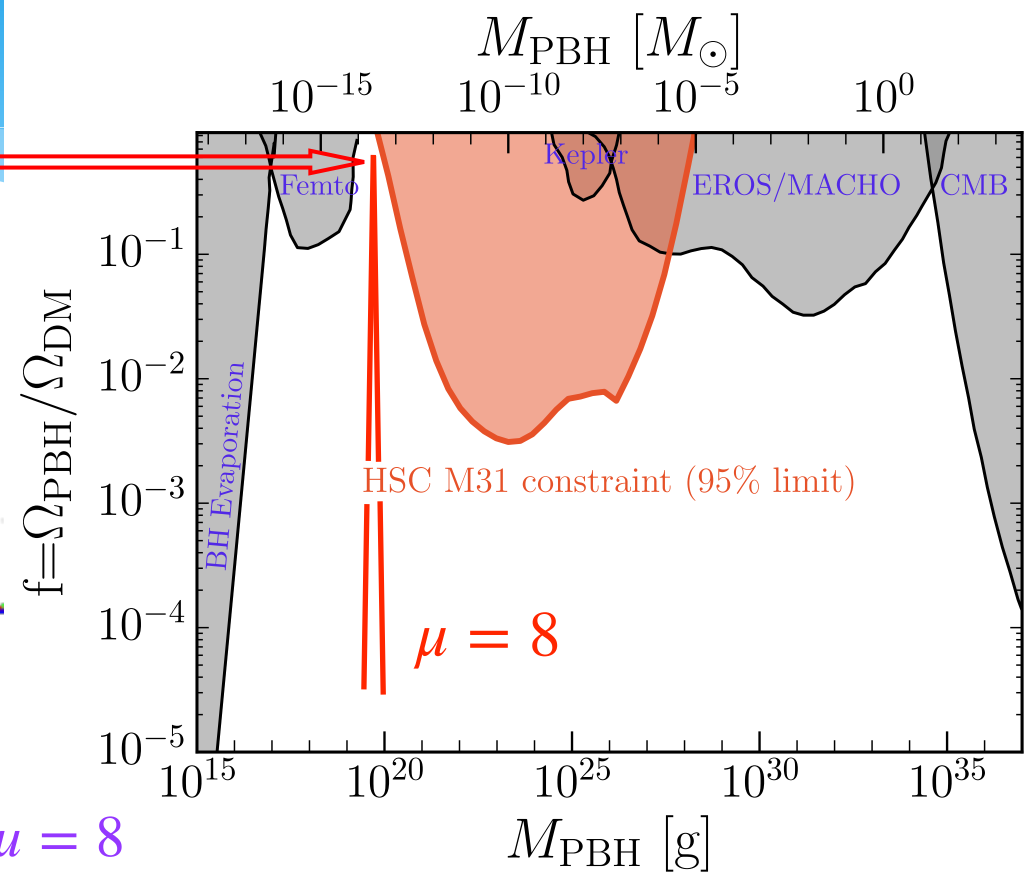


End of the 1st stage of inflation

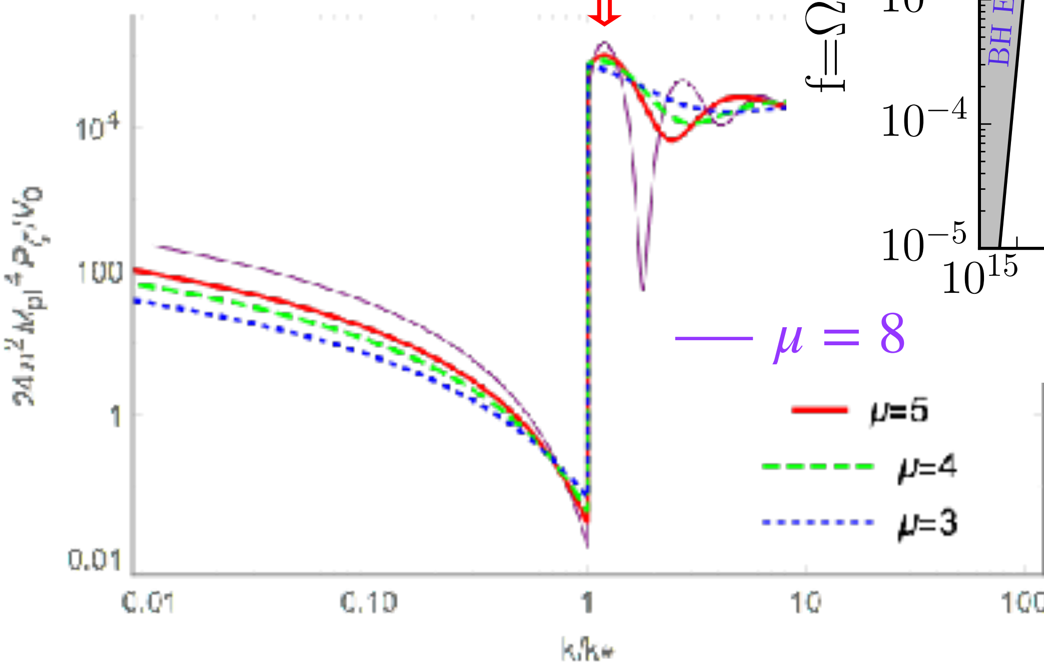
sharp peak in P(k) → spike in f

$$f \propto \exp\left[-\frac{1}{\mathscr{P}(k)}\right]$$

spike



sharp peak



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

2^{nd} order GW constraints on PBH

Saito & Yokoyama ’09, Alabidi et al. ’12, …

- Non-negligible PBH formation means $\mathcal{P}_S(k) \sim 10^{-2.5} - 10^{-2}$

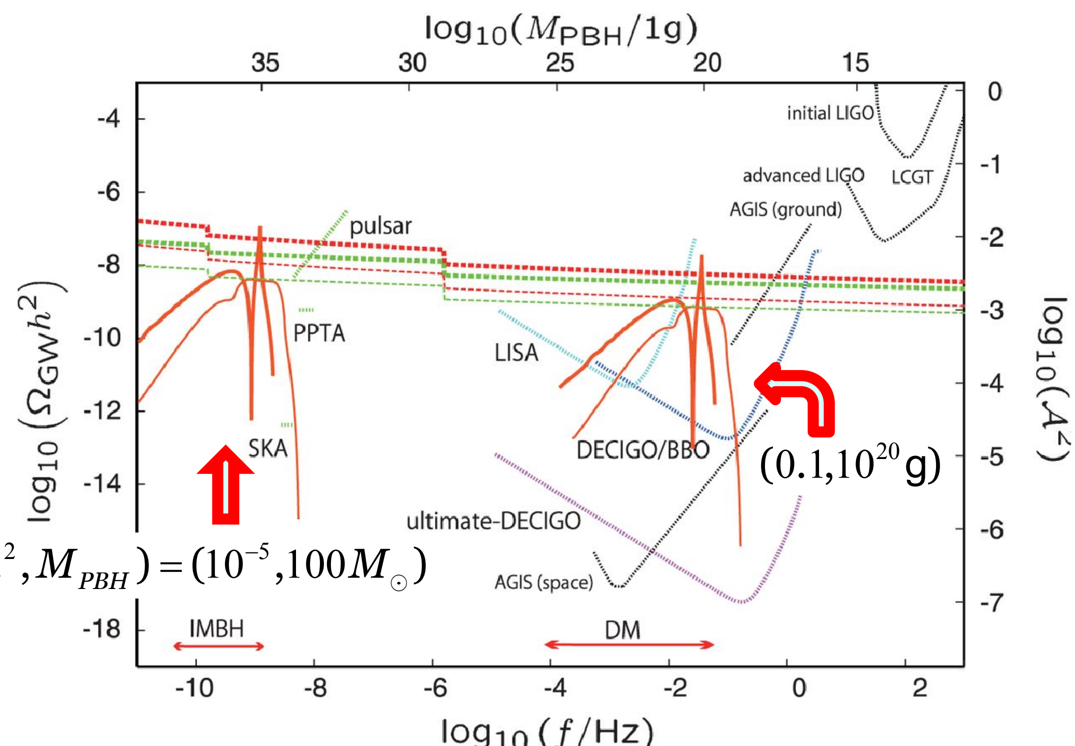
$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - a^{-2}\Delta h_{ij} = S_{ij} \qquad S_{ij} \simeq \frac{1}{a^2}\partial_i \mathcal{R}_c \partial_j \mathcal{R}_c + \cdots \sim \frac{k^2}{a^2}\mathcal{P}_S(k)$$

- GWs are produced with amplitude:

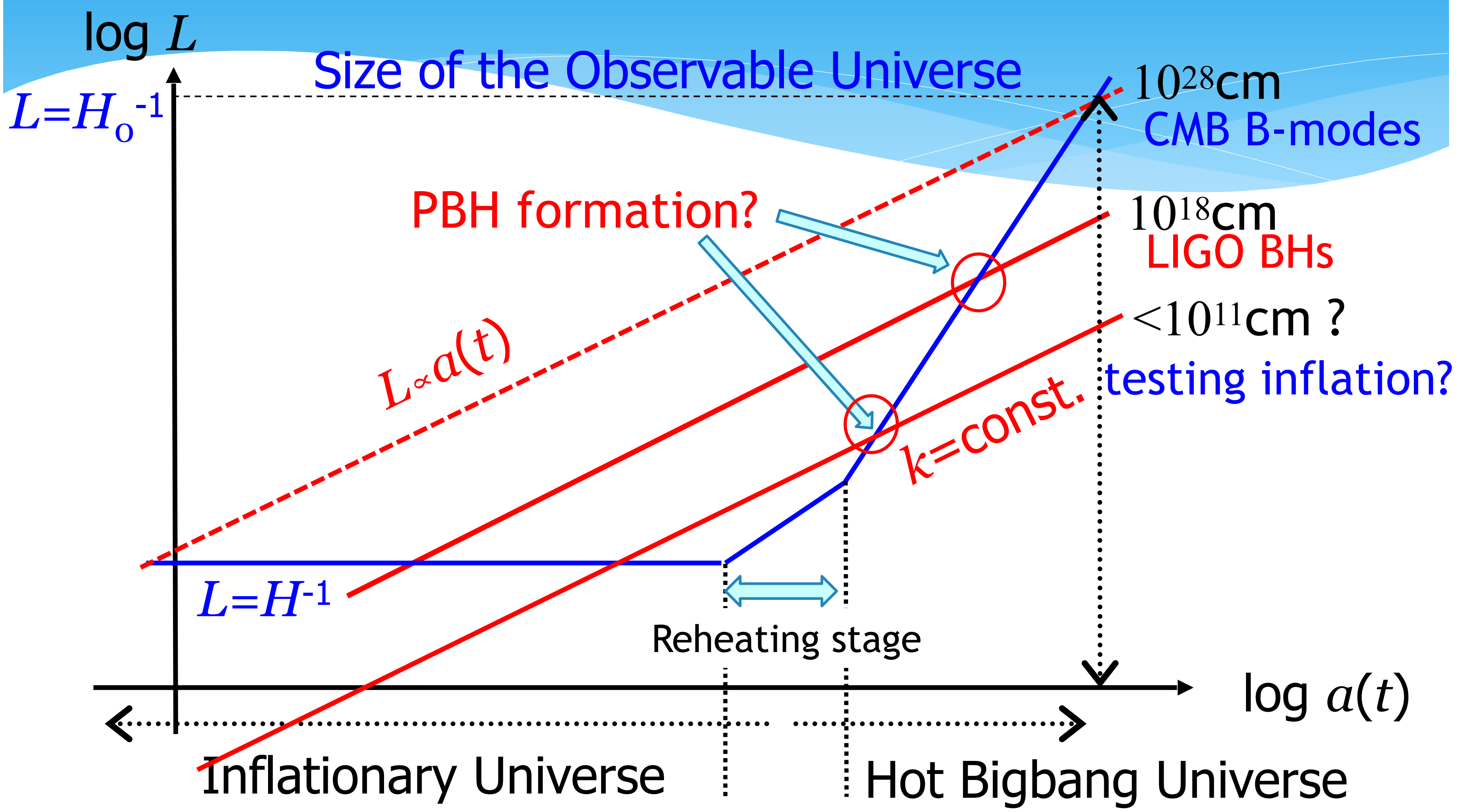
$$h_{ij} \sim \frac{k^2}{a^2 H^2}\mathcal{P}_S(k) \sim \mathcal{P}_S(k)$$

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

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



testing 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.
  advanced GW detectors(+G lensing) will prove/disprove the scenario.

- CDM can be dominated by PBHs of $M \sim 10^{20}$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