Micro Black Holes may be Dark Matter of the Universe

CQeST workshop on
Cosmology and Quantum Spacetime
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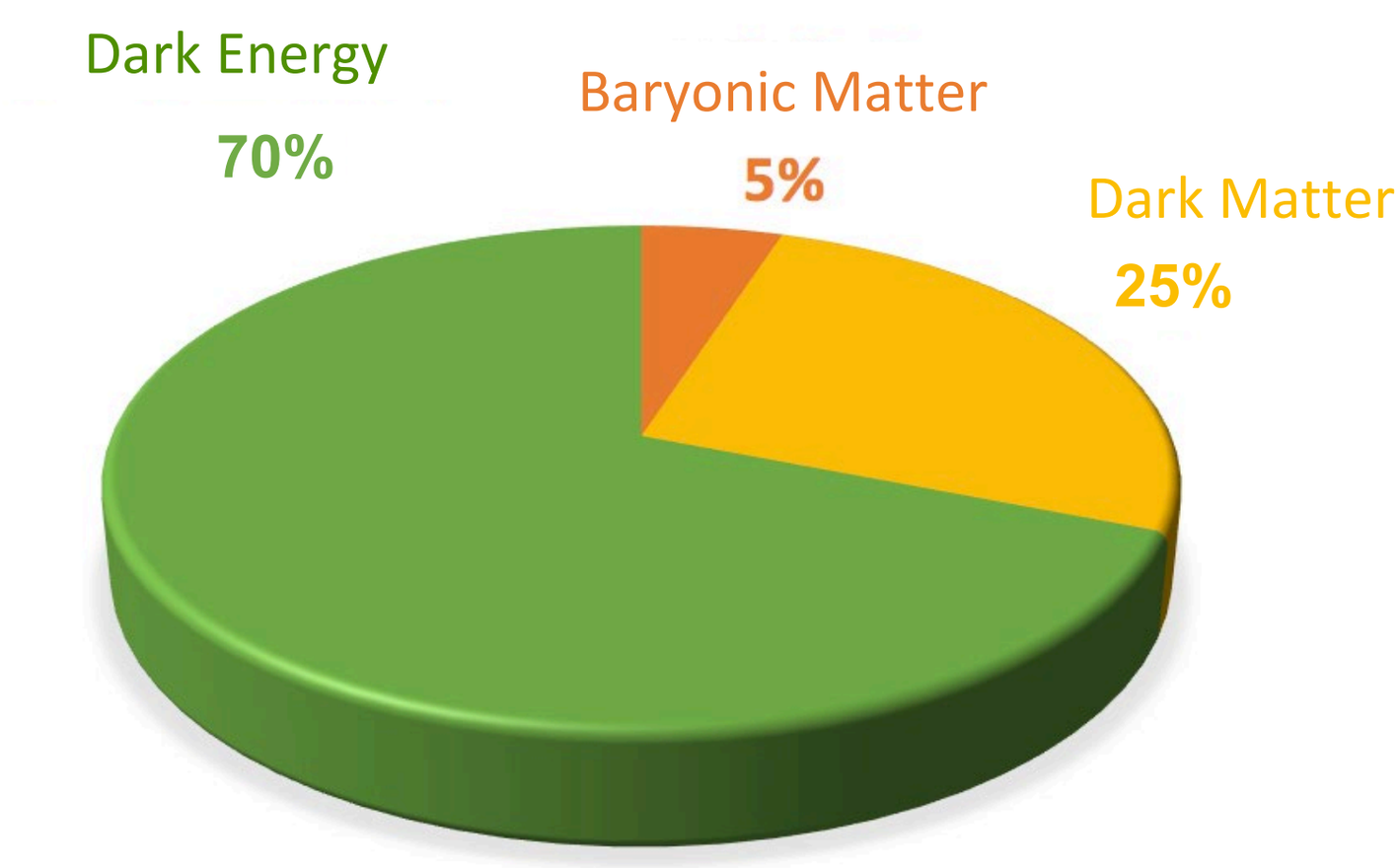
Constituents of the Universe

- normal (baryonic) matter occupies only ~ 5 percent
- dominant component is Dark Energy: completely unknown

→ future issue

- next dominant component is Dark Matter: undiscovered particles?

black holes?



Properties of Dark Matter

necessary properties:

- transparent to light: Transparent matter rather than Dark matter

  - CMB, galactic rotation curves, gravitational lensing,…

  almost non-interacting with normal (baryonic) matter

- halo formation due to gravity: no pressure to stop contraction

  - Large scale structure formation, …

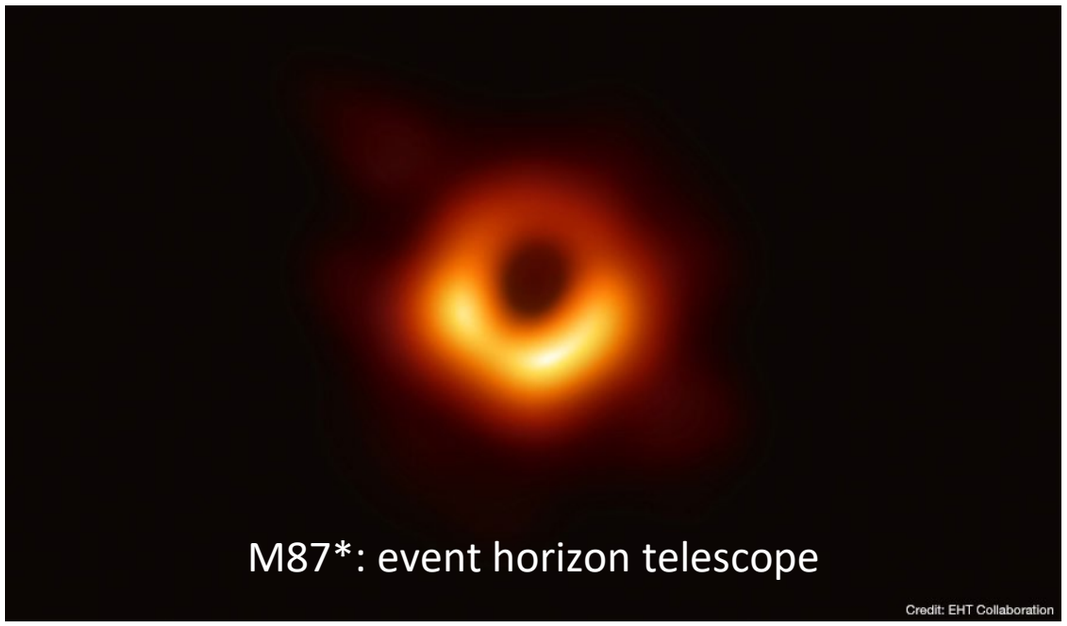
  very cold ⇨ Cold Dark Matter: $w \equiv \frac{p}{\rho} \ll 1$

candidates:

- WIMPs
- ALPs, extremely light bosons
- dark photons, dark gravitons, …
- Black Holes (BHs)!

BHs are one of the best candidates, as they interact only through gravity

“observed” BHs



BH mass = $6.5\times 10^9 M_\odot$

size=100 AU

1AU=1.5x10^{8}km

distance btw Sun and Earth

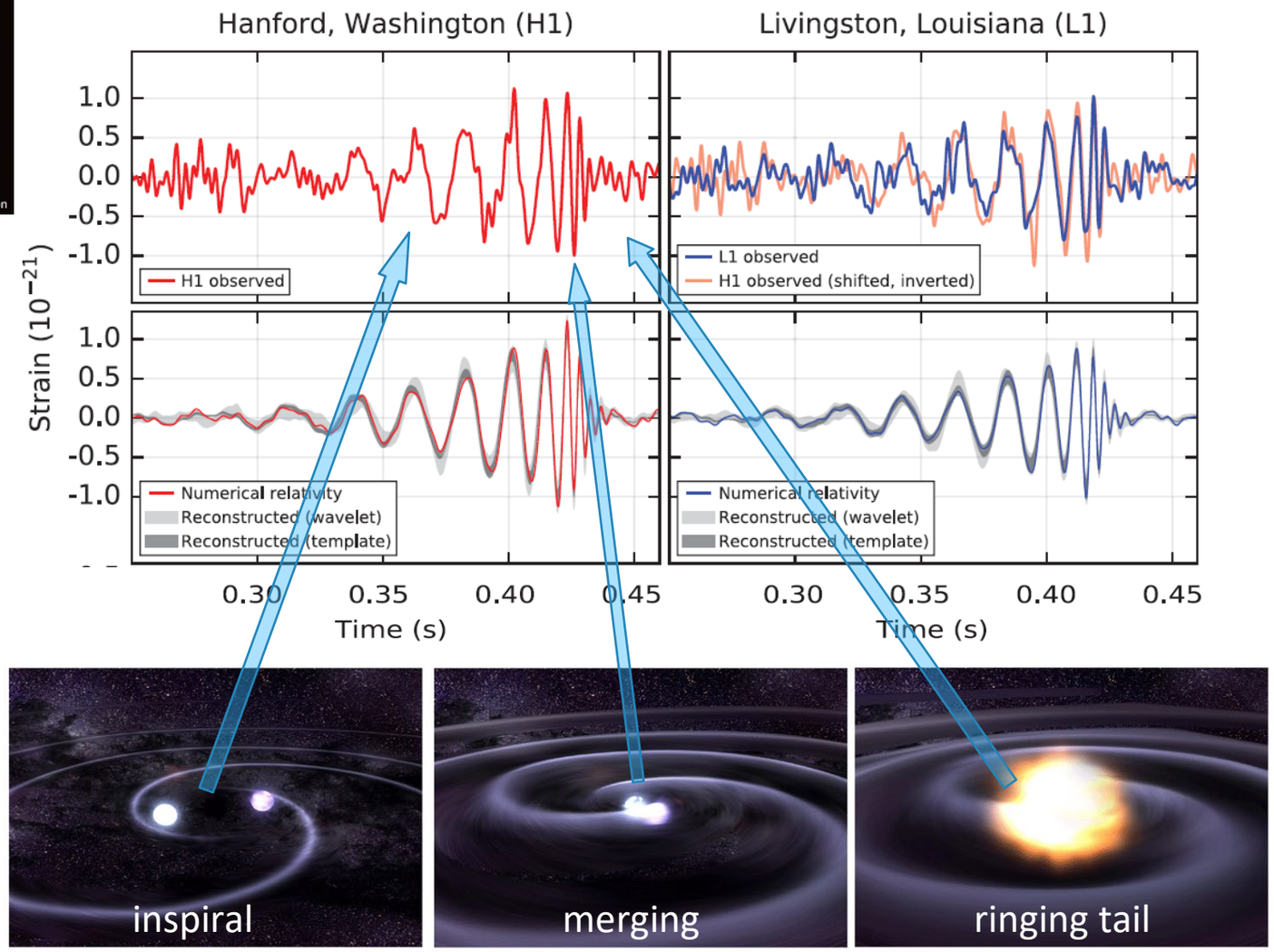
super massive BH

Origin ?

massive BH

BH mass = $30M_\odot$ x 2

size = 200 km



GW140914: LIGO

Primordial BH (PBH)

- BH formed in the very early Universe

  at least, $t < 10^5$ yr or $T > 1$ eV

- most probably, due to large spacetime fluctuations (curvature perturbation) produced from Inflation

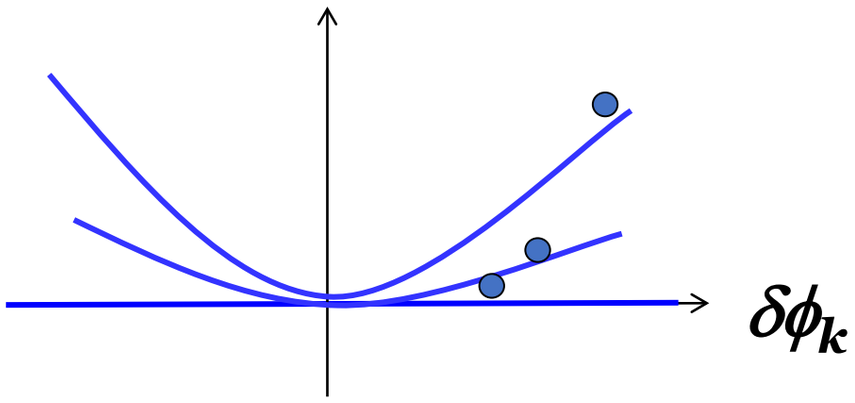
Seed of curvature perturbations

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.

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

$\delta\phi$ obeys Gaussian distribution: $P(\phi) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\delta\phi^2}{2\sigma^2}\right]$

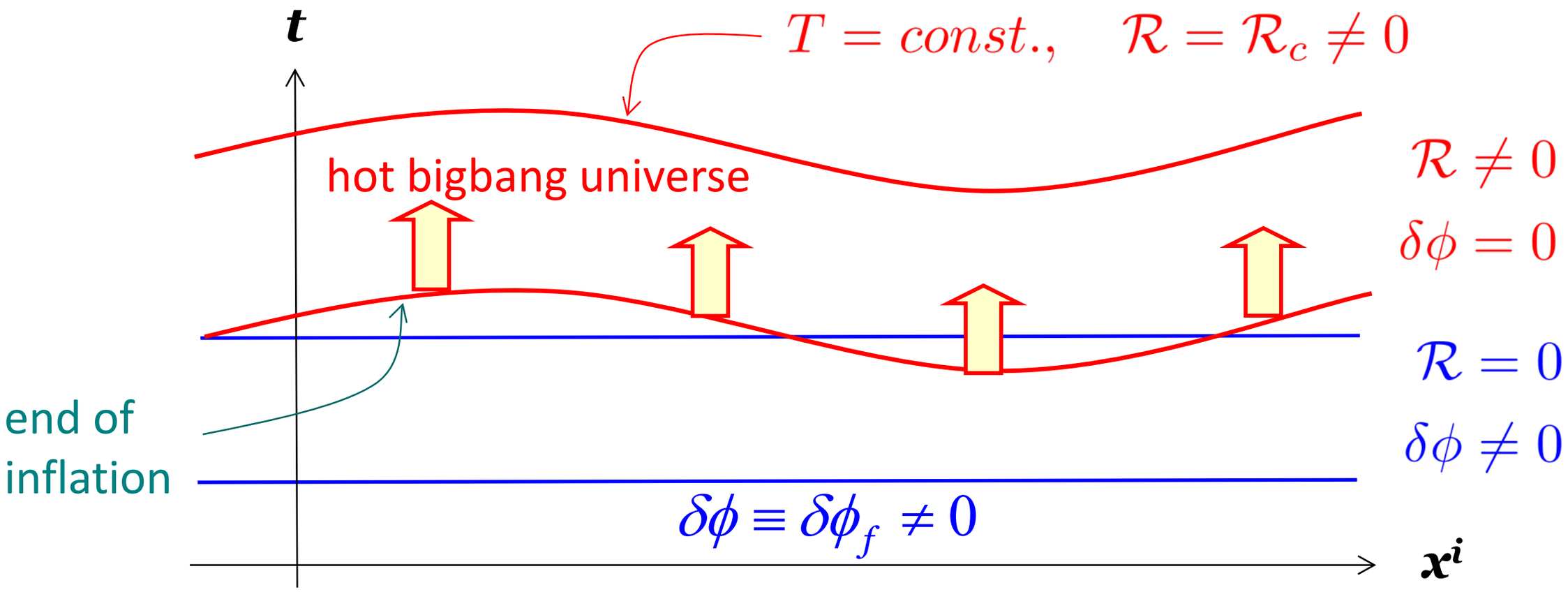
$$\sigma \approx \frac{H}{2\pi}$$

curvature perturbation from quantum fluctuations

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

curvature perturbation on comoving ($\delta\phi$=0) slices $\mathcal{R}_c \sim$ 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 on "comoving" (ϕ =const.) 3-surface.



- The above is for single-field slow-roll inflation. In general, $\mathcal{R}_c = F(\delta\phi_f)$

non-Gaussianity ← NL fcn

probability density function (PDF) of curvature perturbation

($R_c \to R$ here and below)

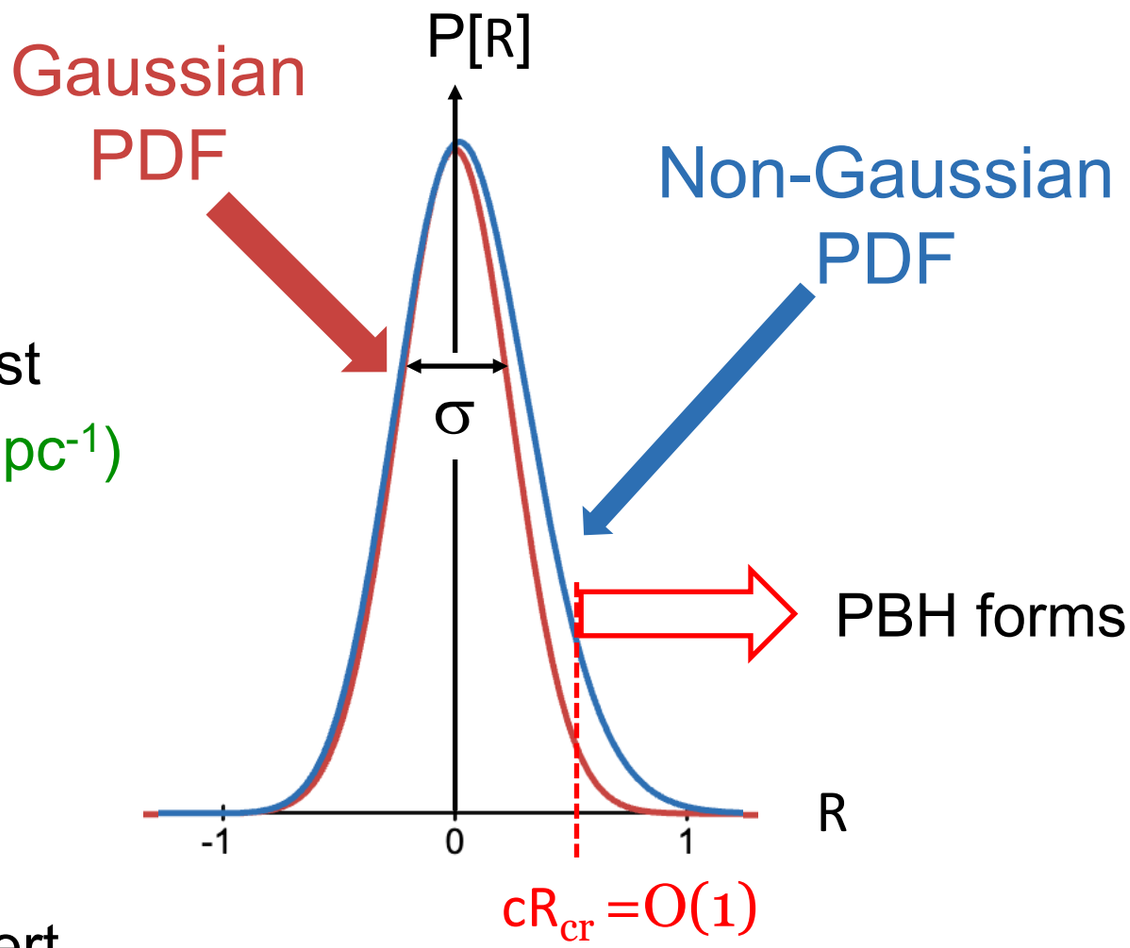
β : fraction that turns into PBH

$$\beta = \int_{\mathcal{R}_{\rm cr}}^{\infty} d\mathcal{R}\, \mathrm{P}[\mathcal{R}] \approx \sqrt{\frac{2}{\pi}} \frac{\sigma}{\mathcal{R}_{\rm cr}} \exp\left(-\frac{\mathcal{R}_{\rm cr}^2}{2\sigma^2}\right)$$

for Gaussian PDF

$\sigma^2 \approx \mathcal{P}(k)$: power spec at scale of interest

(say, $\mathcal{P}(k) \sim 10^{-2}$ at k=1pc^{-1})



- perturbed Einstein eq.

$$^{(3)}R \approx 6H^2 \frac{\delta\rho}{\rho} \quad : \quad ^{(3)}R \approx \frac{4k^2}{a^2}\mathcal{R}$$

↳ curvature pert. ≈ density pert.

$\mathcal{R} \approx \delta\rho/\rho$ at $k^2/a^2 = H^2$

Non-Gaussian tail significantly affects β

cosmological spacetime diagram

log L

$1/H_0$

strong constraints
from CMB & LSS

almost no constraint
on small scales

Rad-dom.
$1/H \sim a^2$

a/H_0

a/k_*

reheating

$\gtrsim$ 20 efolds

a_*

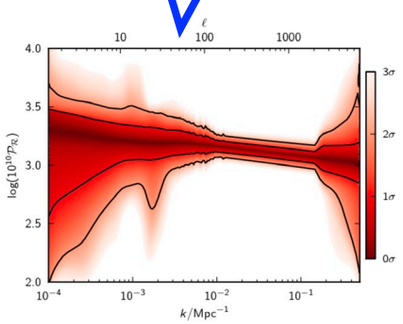
a_{end}

$a_{re\text{-}entry}$

a_{eq}

1

N= log a



Planck

$k_* = Ha_*$

There may be a high peak in the curvature perturbation spectrum

cosmological spacetime diagram

log L

$1/H_0$

probes late stage of inflation

Rad-dom.
$1/H \sim a^2$

a/H_0

a/k_*

reheating

$\gtrsim$ 20 efolds

a_*

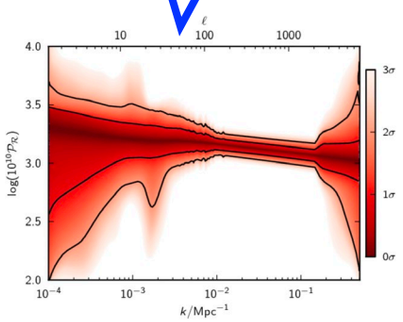
a_{end}

$a_{re-entry}$

a_{eq}

1

N= log a



$k_* = Ha_*$

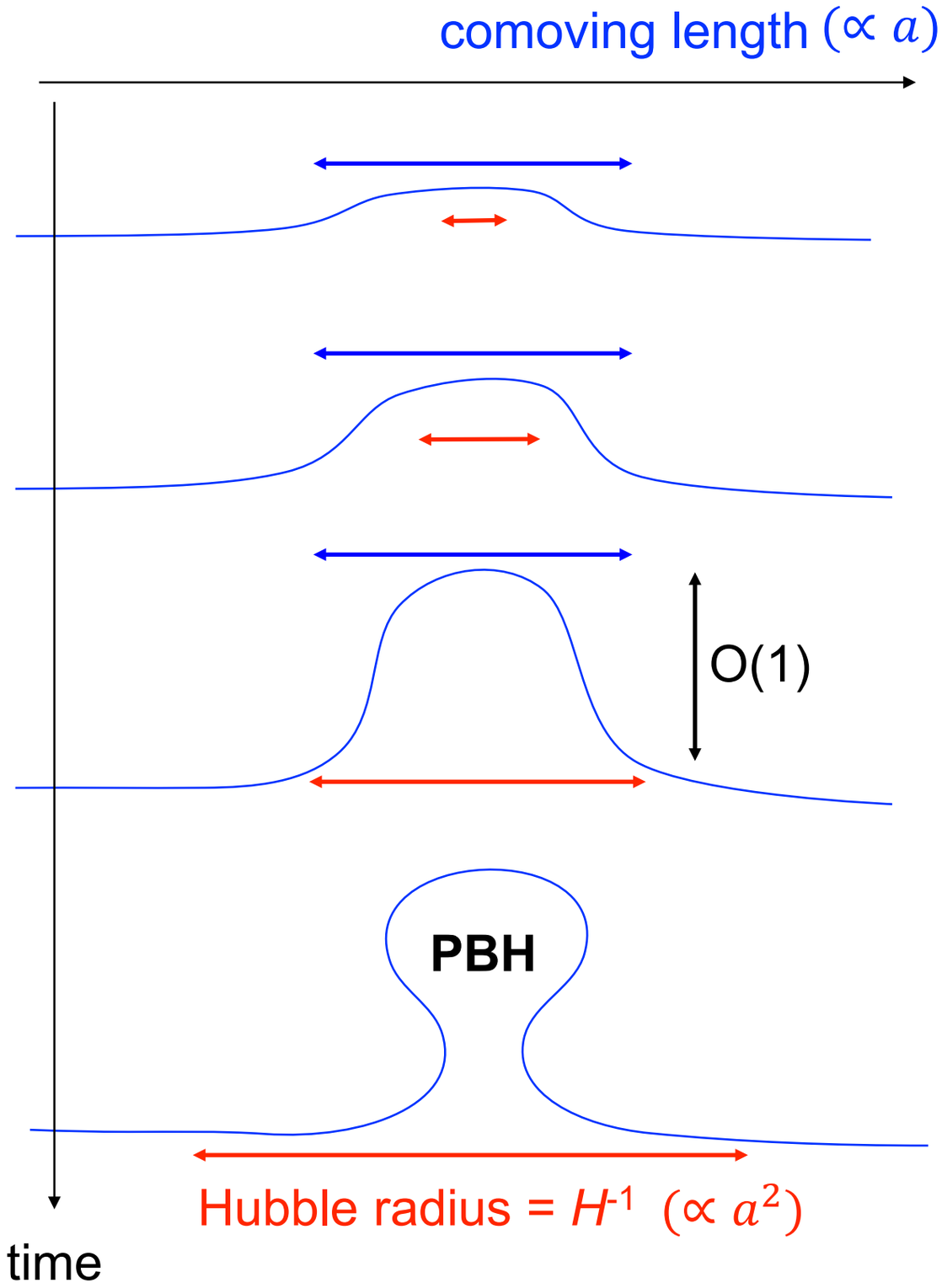
The peak re-enters horizon during radiation era.
PBH will form if the amplitude is 0(1).

Carr and Hawking ('74)

PBH in a nutshell

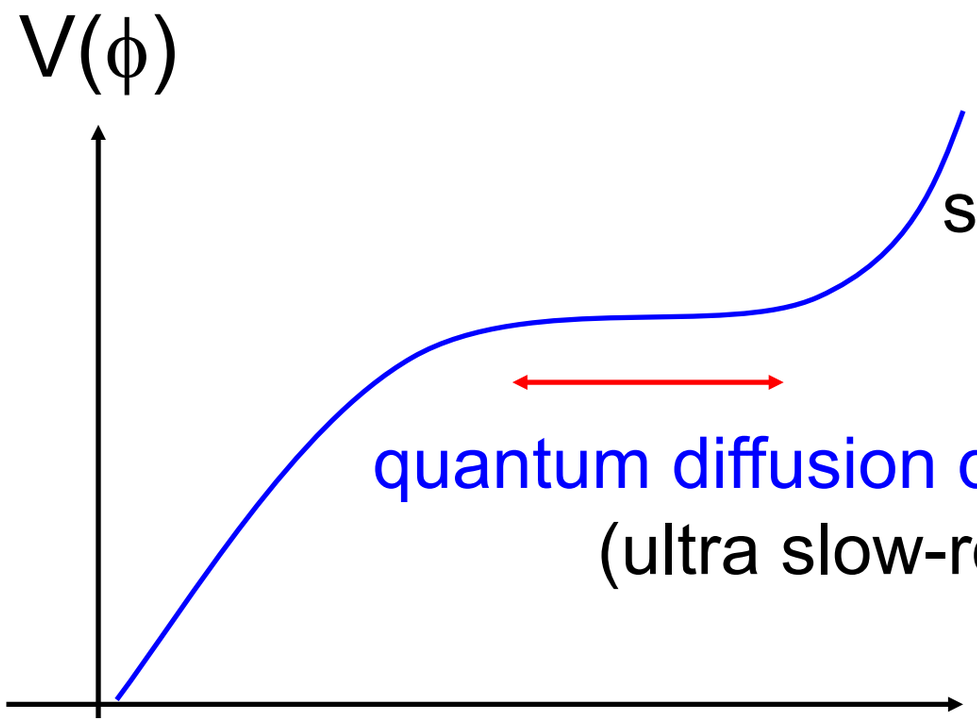
- Primordial Black Holes (PBHs) are those formed in the very early universe, conventionally when the universe was radiation-dominated.
- Presumably they originate from a large positive curvature perturbation produced during inflation (which hence should be a rare event).
- For a BH to form during radiation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

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



model with enhanced power spectrum

Pattison, Vennin, Wands & Assadullahi, 2101.05741, …



$$\delta\phi \gtrsim \frac{\dot{\phi}}{H}$$

$\frac{H}{2\pi}$ vacuum fluctuations

classical background motion

$$\mathcal{R} \approx -\frac{H}{\dot{\phi}}\delta\phi = O(1)$$

tail of the PDF can be exponentially enhanced: $e^{-c\mathcal{R}}$ instead of $e^{-c\mathcal{R}^2}$

Gaussian PDF

→ non-Gaussian PBH formation

exponential tail is quite common in featured potentials

Pi & MS, 2211.13932

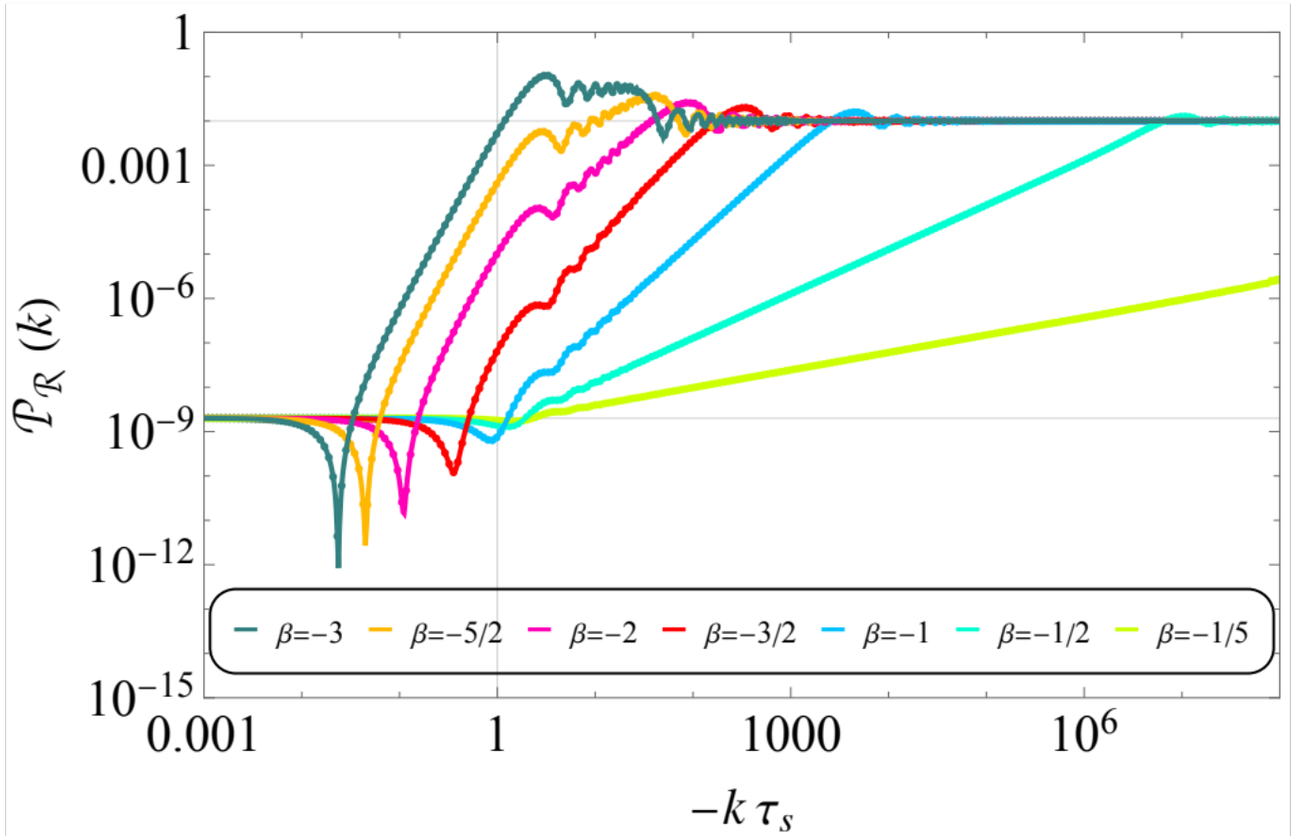
PDF & Power spectrum for featured potential

PDF: $$P(\mathcal{R}) = \frac{|\lambda_- \varphi| e^{\lambda_- \mathcal{R}}}{\sqrt{2\pi}\sigma_{\delta\varphi}} \exp\left[-\frac{\varphi^2\left(e^{\lambda_- \mathcal{R}}-1\right)^2}{2\sigma^2_{\delta\varphi}}\right]$$

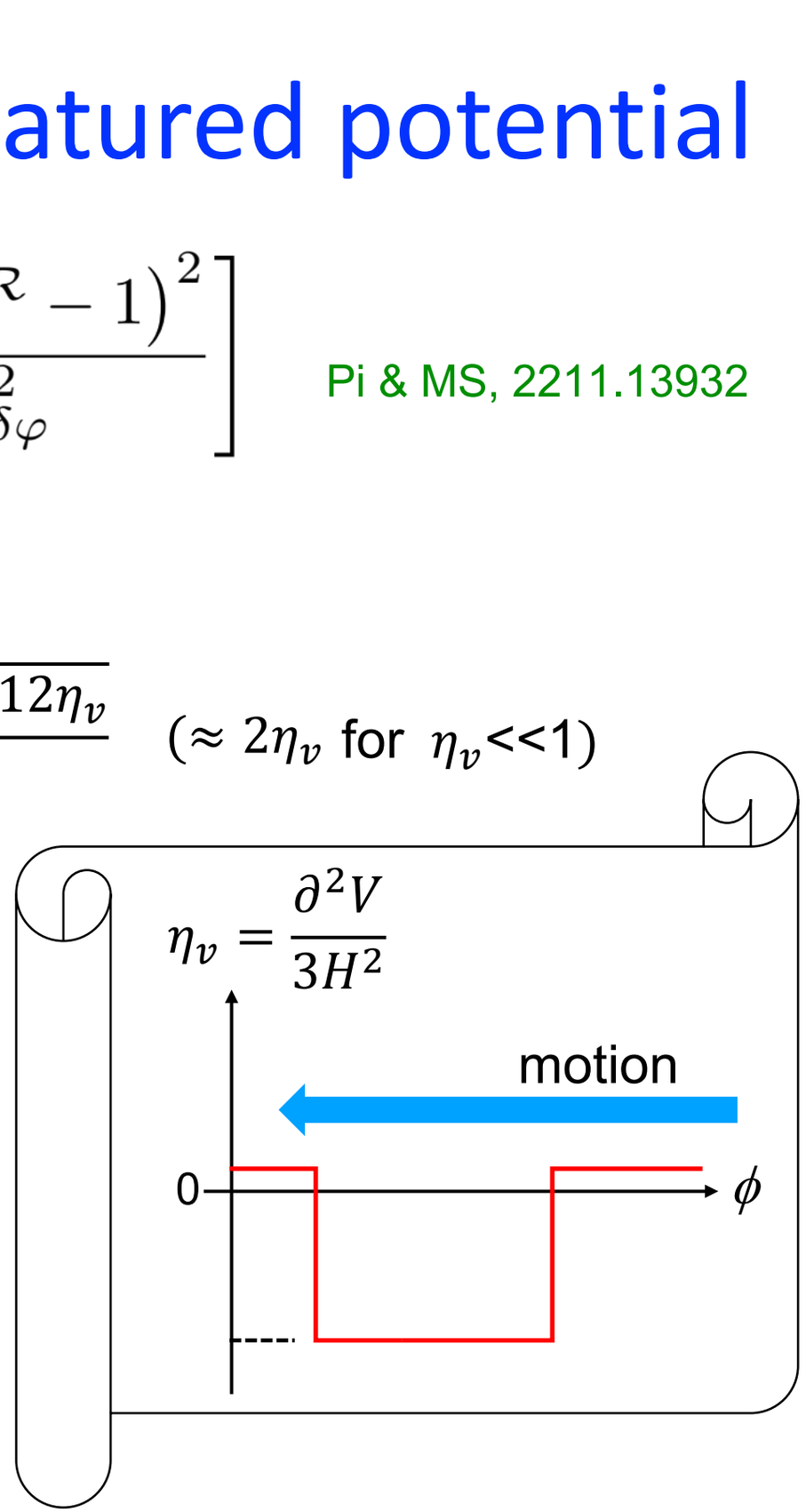
Pi & MS, 2211.13932

dominates the tail when $\lambda_-<0$

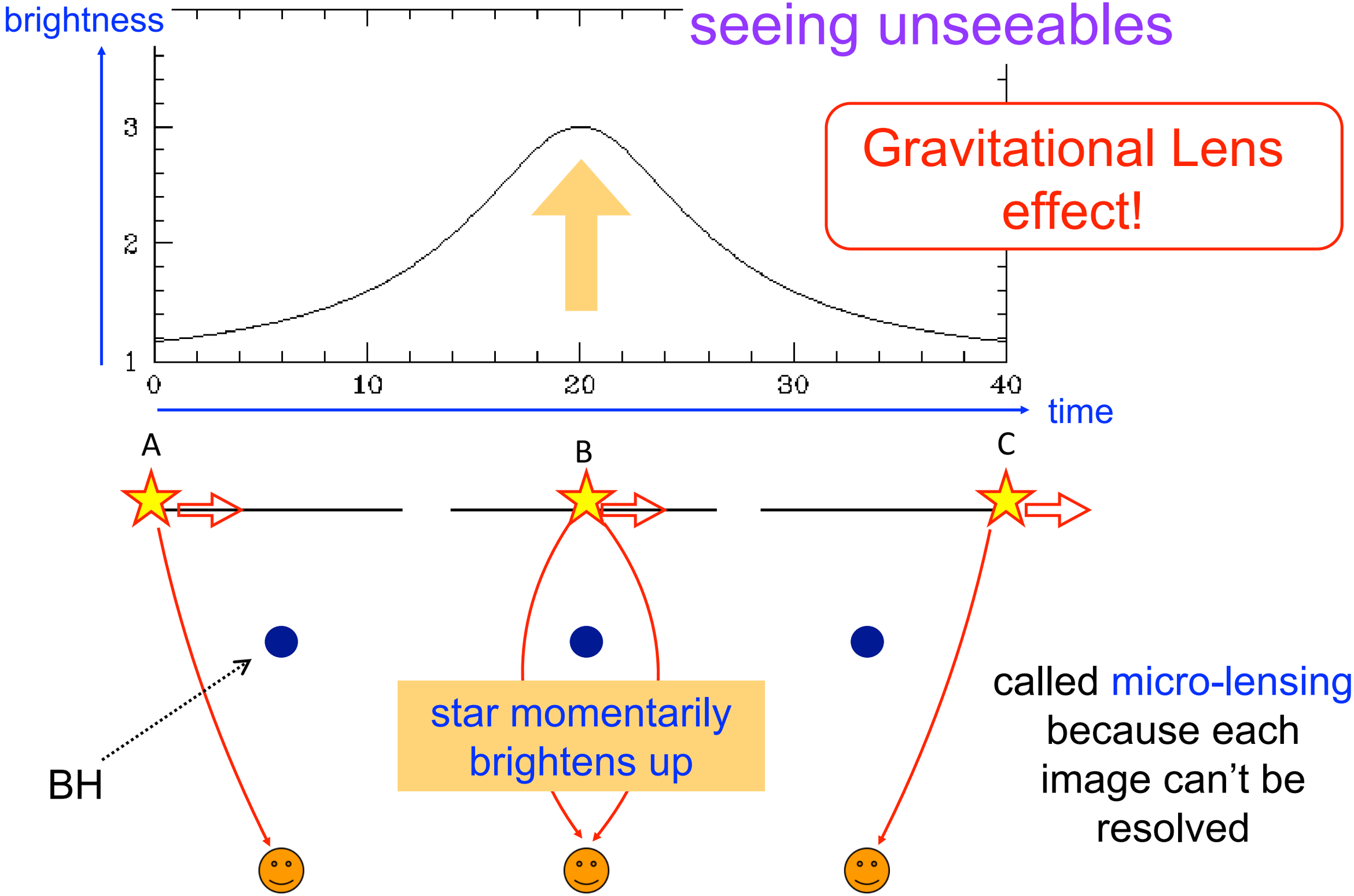
Power spectrum: $$\beta = \lambda_- = \frac{3-\sqrt{9-12\eta_v}}{2} \quad (\approx 2\eta_v \text{ for } \eta_v<<1)$$



Motohashi, Pi, Tada, Wang, 2606.24111

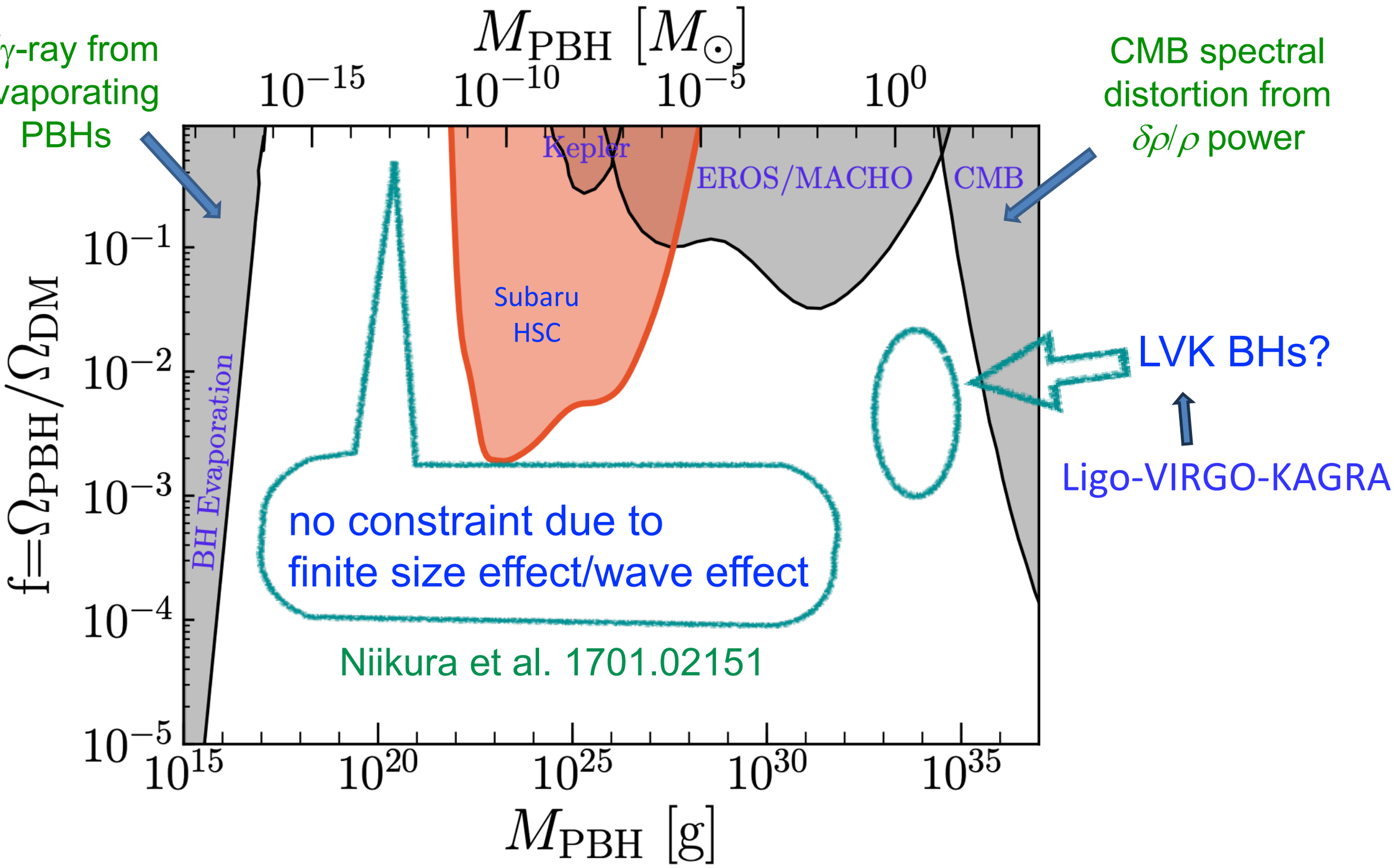


Searching for PBHs



called micro-lensing because each image can't be resolved

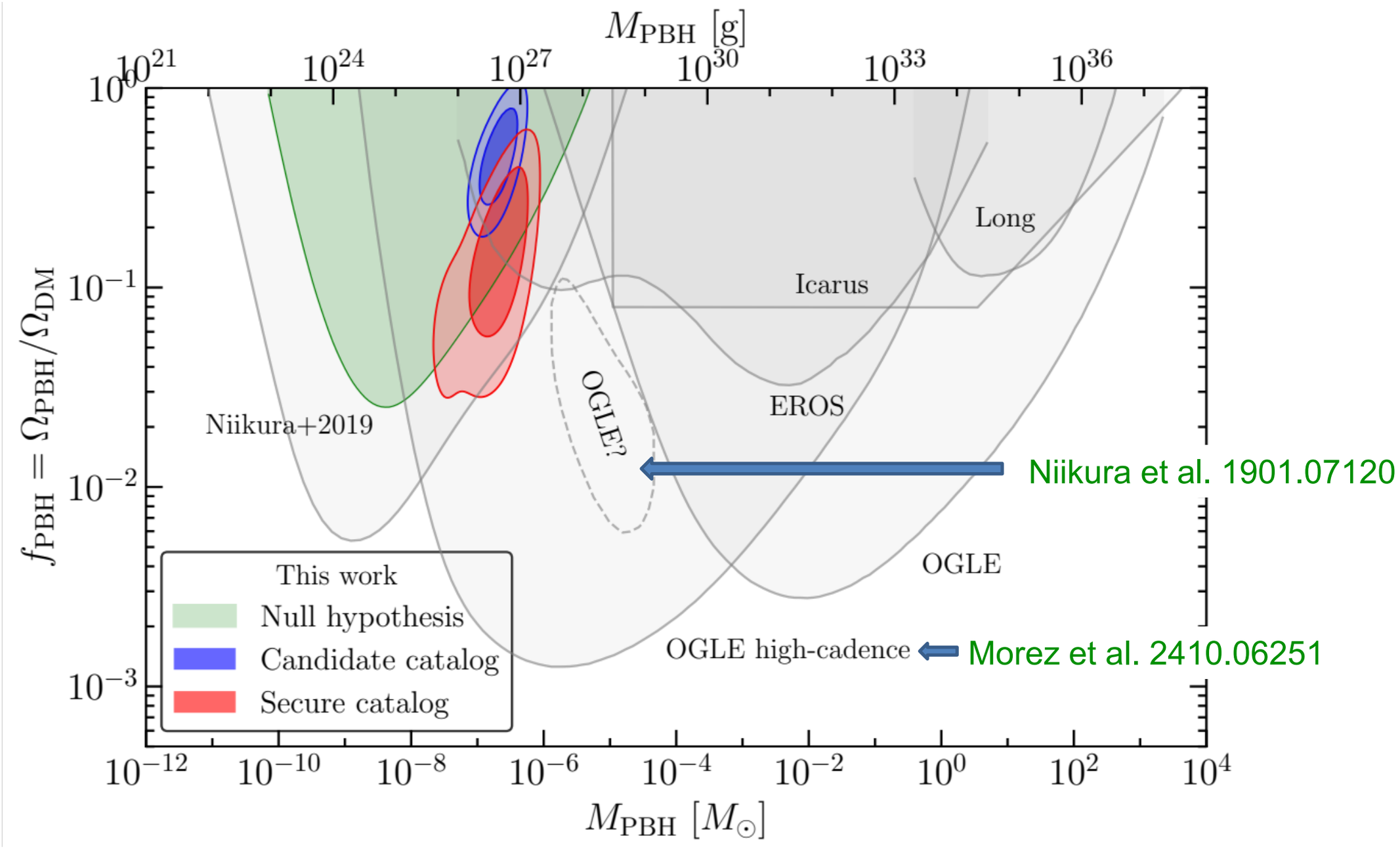
observational constraints



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

recent updates

Sugiyama et al. 2602.05840



Niikura et al. 1901.07120

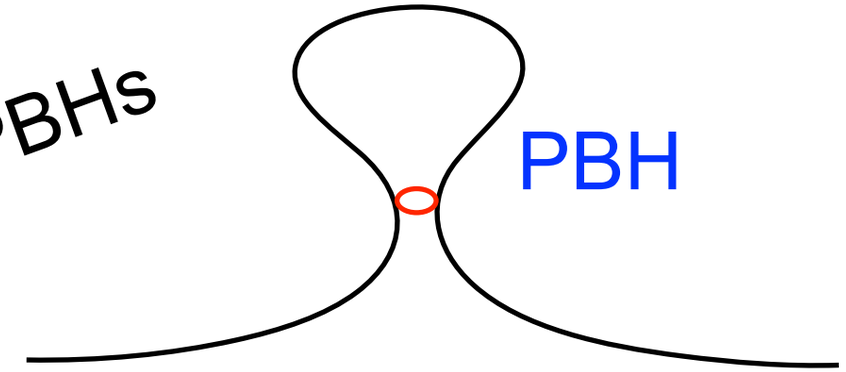
Morez et al. 2410.06251

- Sugiyama et al. found 12 (4 secure) microlensing candidates.
- Earth mass PBHs could be CDM of the Universe!

GWs capture PBHs!

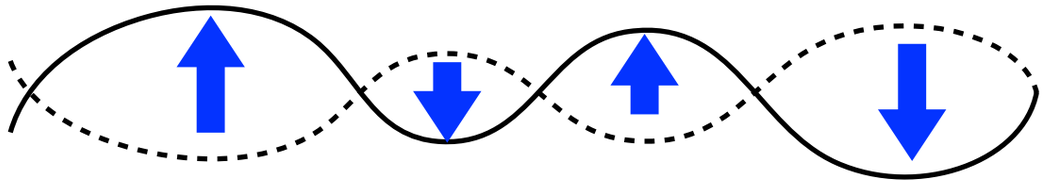
curvature perturbation

large peaks form PBHs

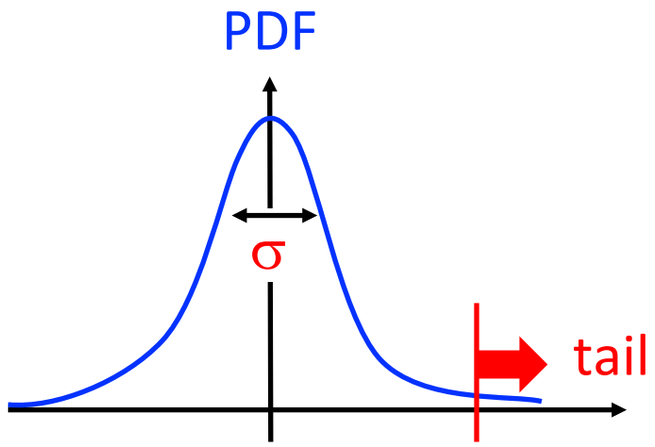


PBHs probe tail of PDF

NL effect induces GWs



spacetime oscillations



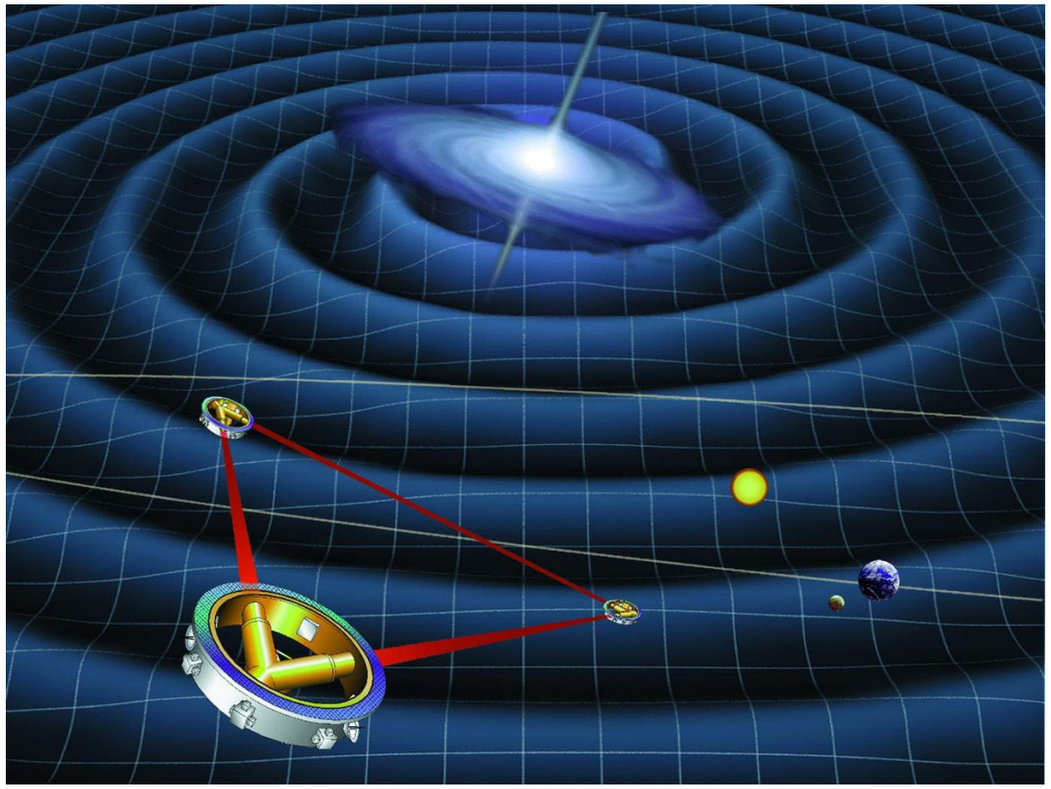
induced GWs probe power spectrum (σ^2)

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

⇨ Background GWs in LISA/Taiji/TianQin band

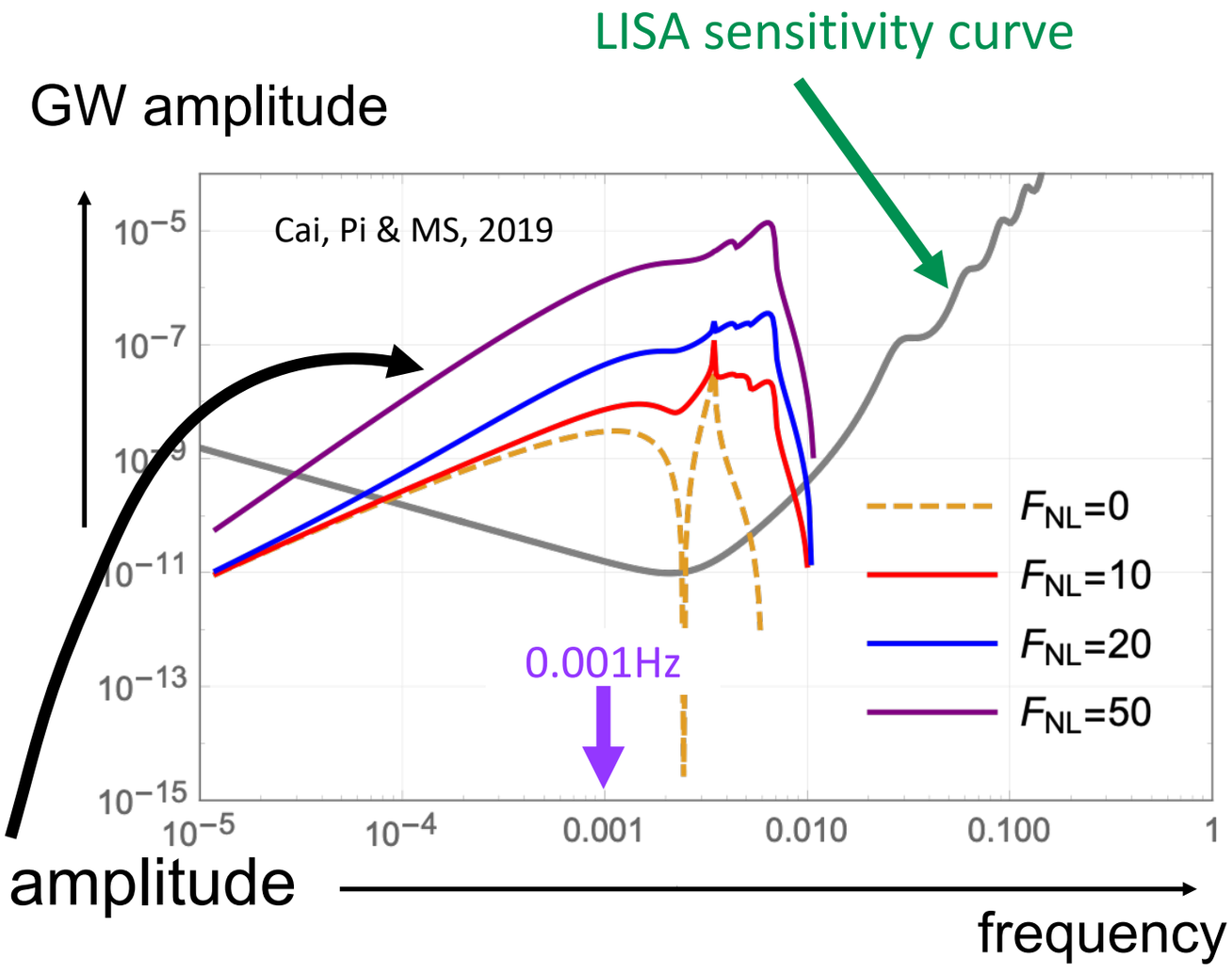
space-based gravitational wave detectors

GW Observatory in Space



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

Taiji/TianQin 203X ? (China)
arm length:
3,000,000 km/1,732,000 km



PBH=CDM scenario will be proved/disproved!

Summary

Micro PBHs may be Dark Matter of the Universe

- normal (baryonic) matter constitutes only 5%

  visible components like stars and galaxies

- 70% is Dark Energy

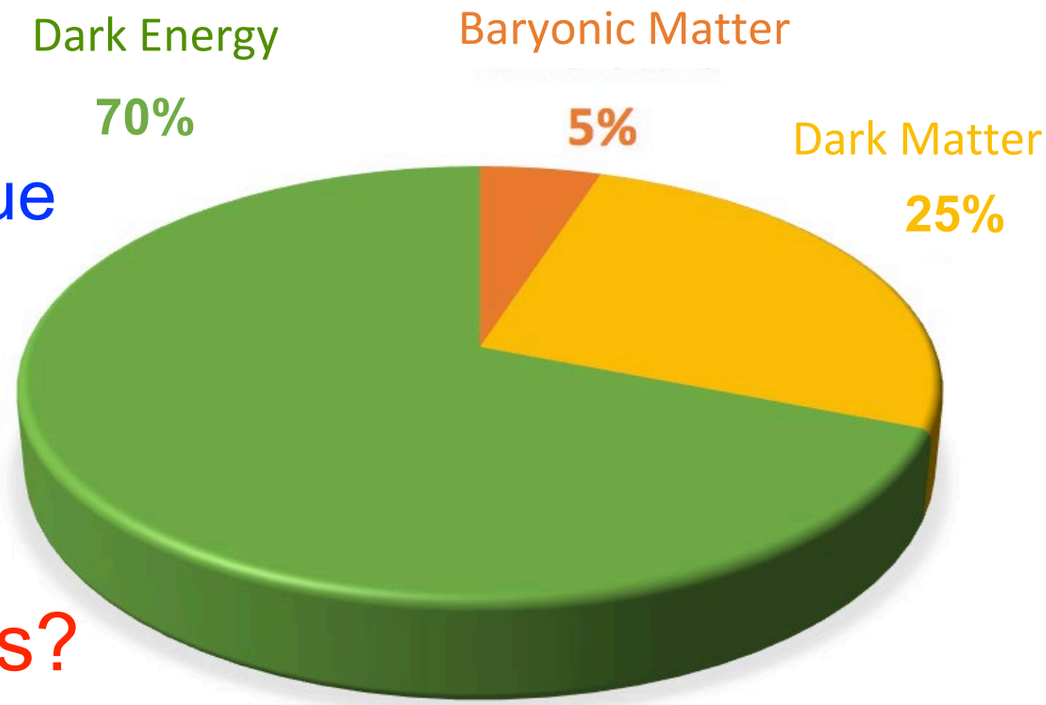
  completely unidentified: future issue

- 25% is Dark Matter

  unidentified: WIMPs? ALPs?

  or

  microscopic PBHs?



10^{-6} -10^{-4} mm

10^{18} -10^{20} kg

Obs of GW background will tell us the answer!