2023.12.05 @ Kashiwa Dark Matter Symposium 2023

The Present & Future of Primordial Black Holes as Dark Matter

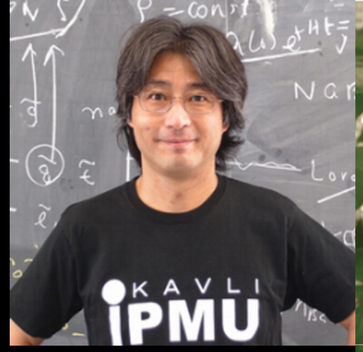
Nagoya U. IAR Yuichiro TADA

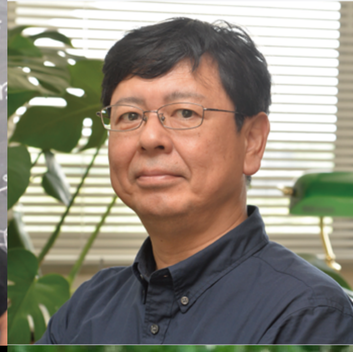
Escrivà, Kühnel , YT “Primordial Black Holes” (2022)

"Black Holes in the Era of Gravitational-Wave Astronomy"

Contents

Yuichiro TADA 多田 祐一郎






'08–'12	Undergrad @ UTokyo
'12–'17	PhD w/ H. Murayama (IPMU), M. Kawasaki (ICRR)
'17–'18	PD w/ S. Renaux-Petel (IAP)
'18–'21	JSPS PD w/ N. Sugiyama (Nagoya)
'21–	YLC Assistant Prof. w/ K. Ichiki (Nagoya)

- on Early Universe Inflation, PBH, GW, ...

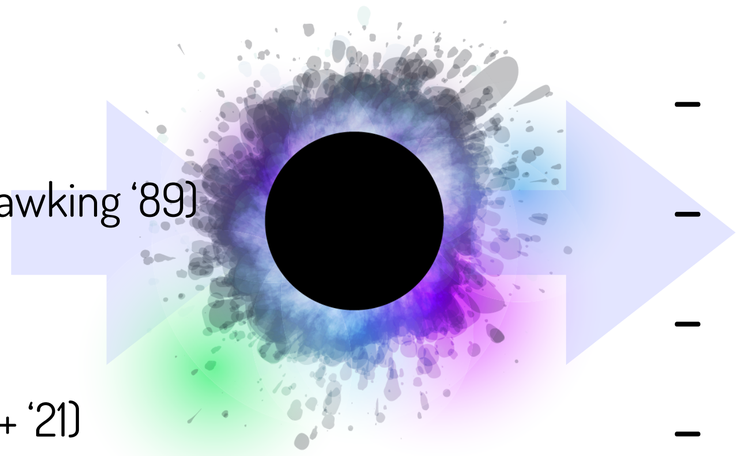
2. PBH as DM

Primordial BH

Carr & Hawking '74

- $\sim \mathcal{O}(1)$ Primordial PTBs (Carr '75)
- Isocurvature (Dolgov & Silk '93)
- Quark Confinement (Dvali+ '21)
- Collapse of topological defect (Hawking '89)
- Bubble collision (Hawking+ '82)
- Particle trapping in bubble (Baker+ '21)
- Asynchronous 1st PT (Liu+ '21)
- Scalar 5th force (Flores & Kusenko '20)

⋮



before Star Form.

Primordial Black Hole

- Dark Matter (Chapline '75)
- LVK merger GW? (Sasaki+ '16)
- SMBH seeds? (Düchting '04)
- OGLE lensing obj.? (Niikura+ '19)
- Planet 9? (Scholtz & Unwin '19)
- Trigger of r-process? (Fuller+ '17)
- Baryogenesis? (Baumann+ '07)
- JWST luminous gals? (Hutsi+ '22)

⋮

Primordial BH

Carr & Hawking '74

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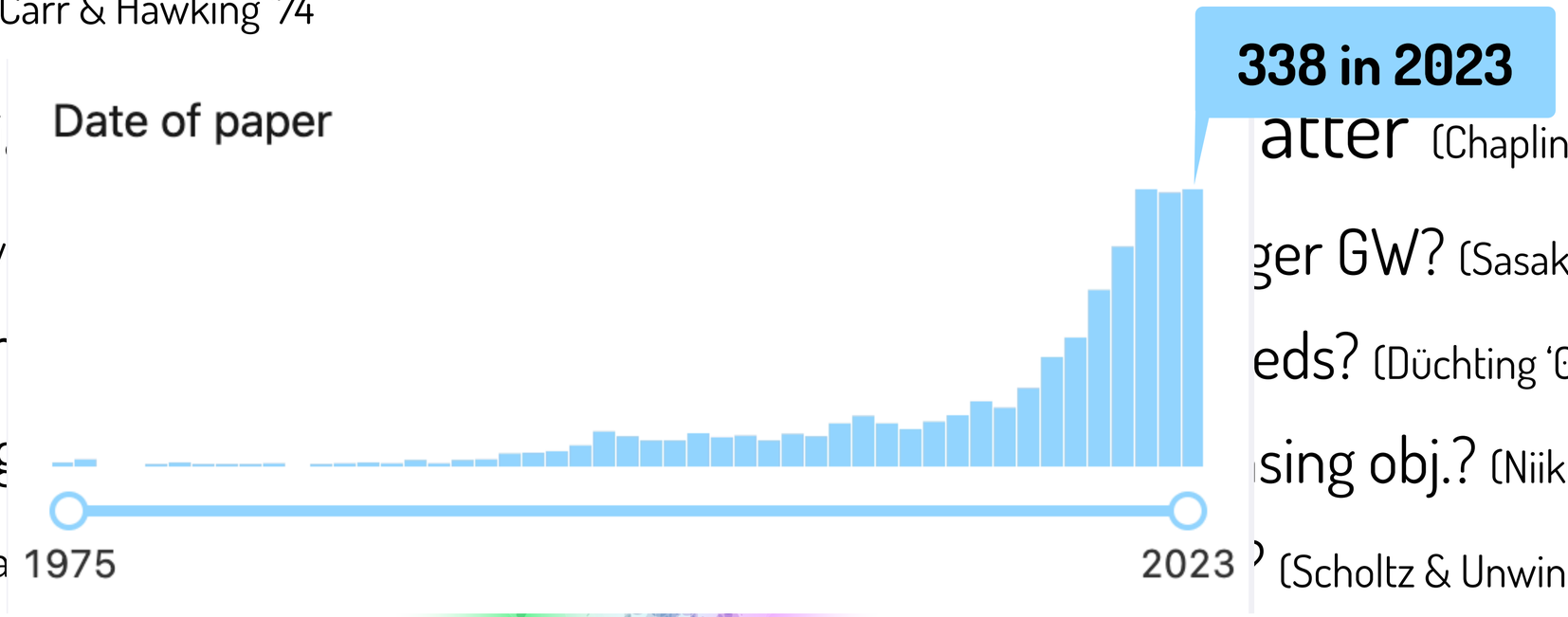

- atter (Chapline '75)
- ger GW? (Sasaki+ '16)
- eds? (Düchting '04)
- sing obj.? (Niikura+ '19)
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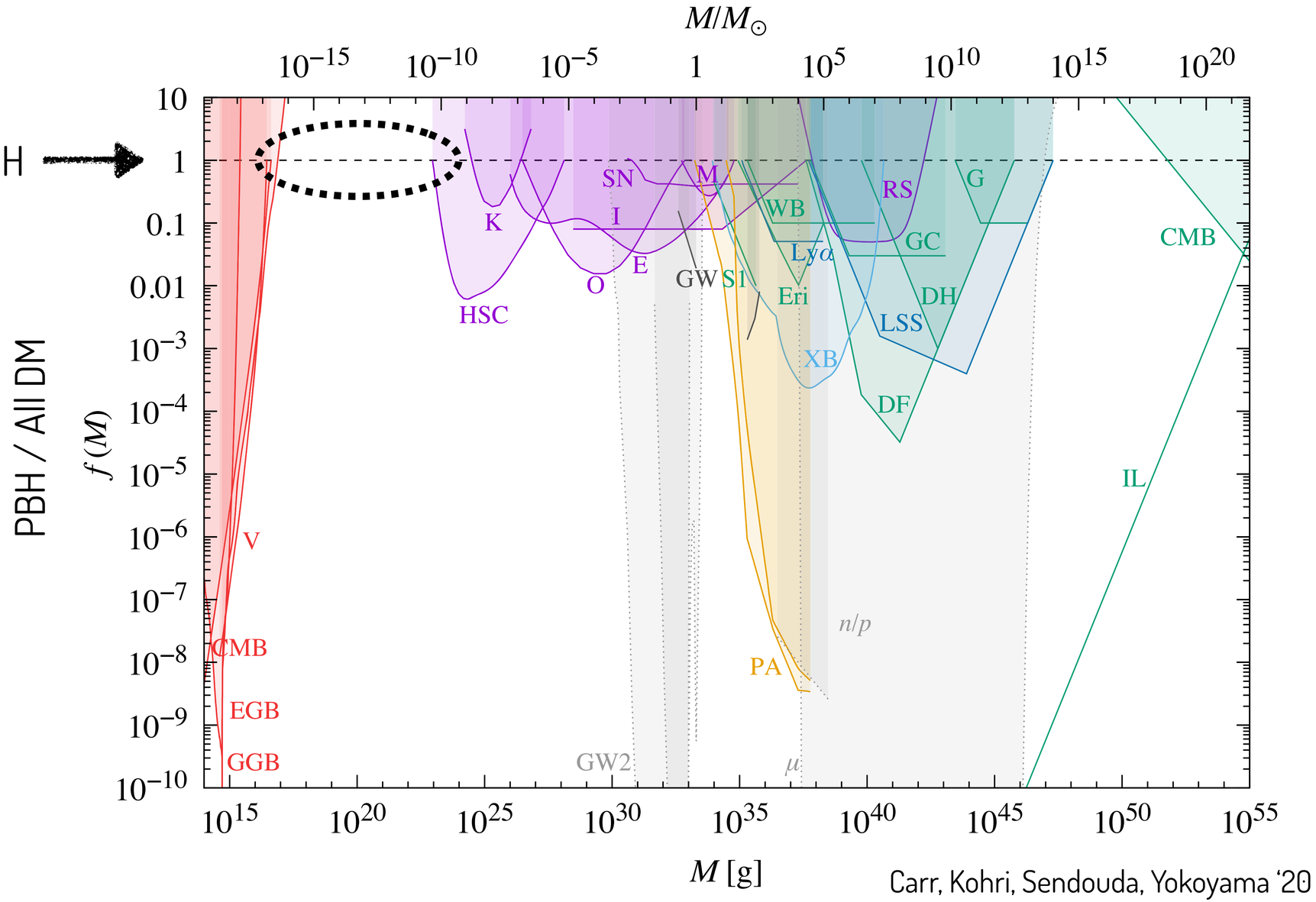
- Trigger of r-process? (Fuller+ '17)
- Baryogenesis? (Baumann+ '07)
- JWST luminous gals? (Hutsi+ '22)

before Star Form.

Primordial Black Hole

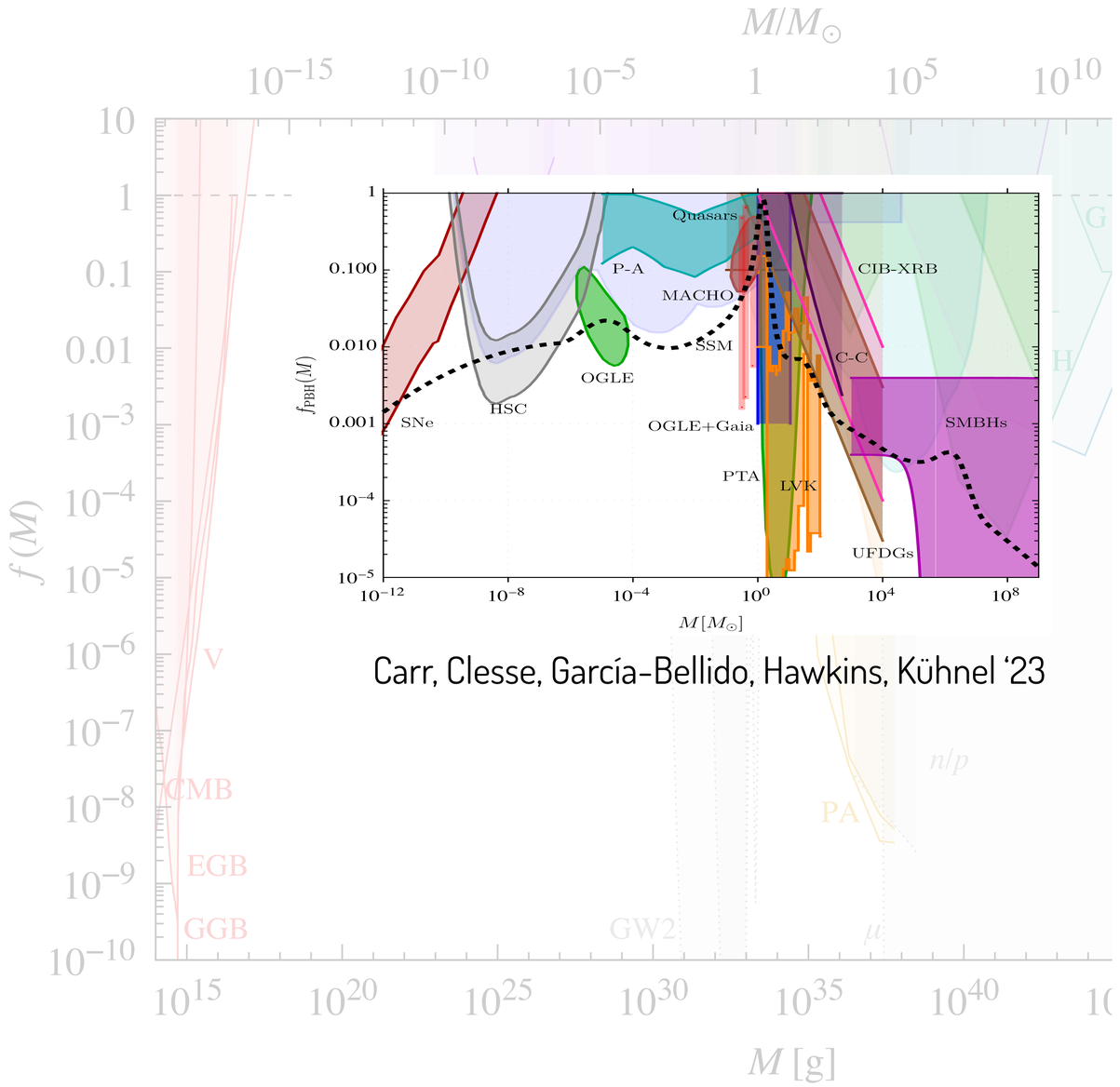
Obs. Consts.

All DM = PBH

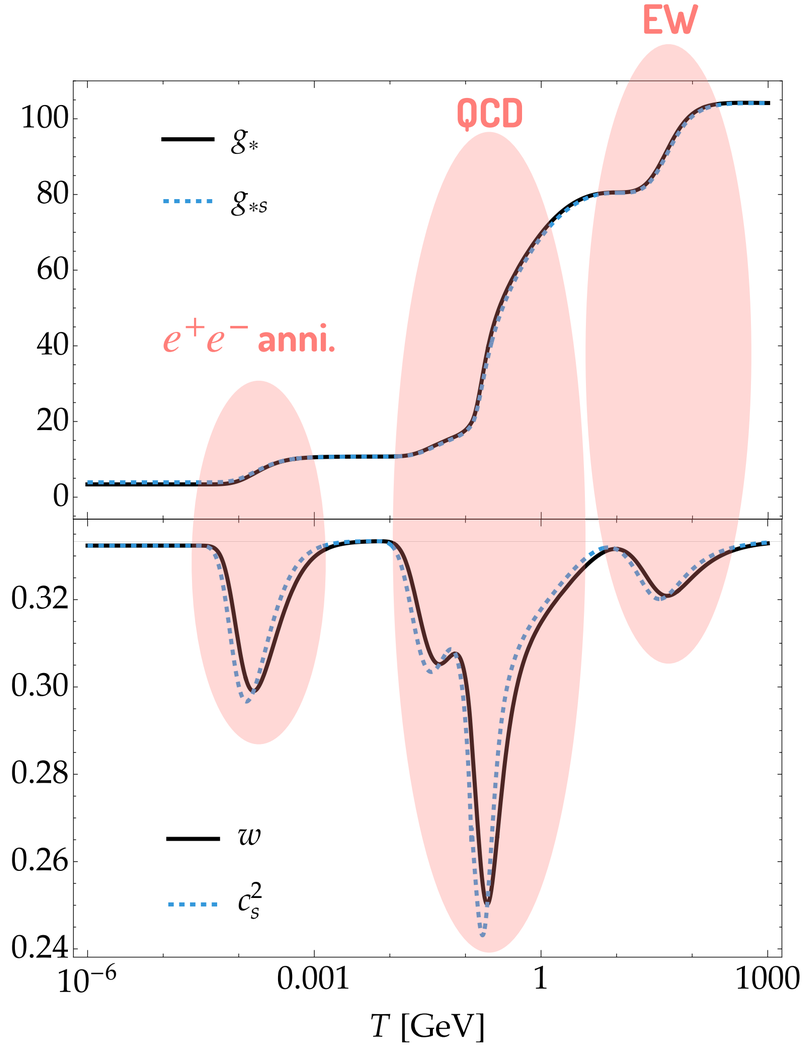


Carr, Kohri, Sendouda, Yokoyama '20

Positivist Perspective?



Carr, Clesse, García-Bellido, Hawkins, Kühnel '23



cf. Saikawa & Shirai '18

Evidence? 1

$$M < M_\odot$$

FAR [yr^{-1}]	ln $\mathcal{L}$	UTC time	mass 1 [$M_\odot$]	mass 2 [$M_\odot$]	spin1z	spin2z	Network SNR	H1 SNR	L1 SNR
0.1674	8.457	2017-03-15 15:51:30	3.062	0.9281	0.08254	-0.09841	8.527	8.527	-
0.2193	8.2	2017-07-10 17:52:43	2.106	0.2759	0.08703	0.0753	8.157	-	8.157
0.4134	7.585	2017-04-01 01:43:34	4.897	0.7795	-0.05488	-0.04856	8.672	6.319	5.939
1.2148	6.589	2017-03-08 07:07:18	2.257	0.6997	-0.03655	-0.04473	8.535	6.321	5.736

Phukon+ '21

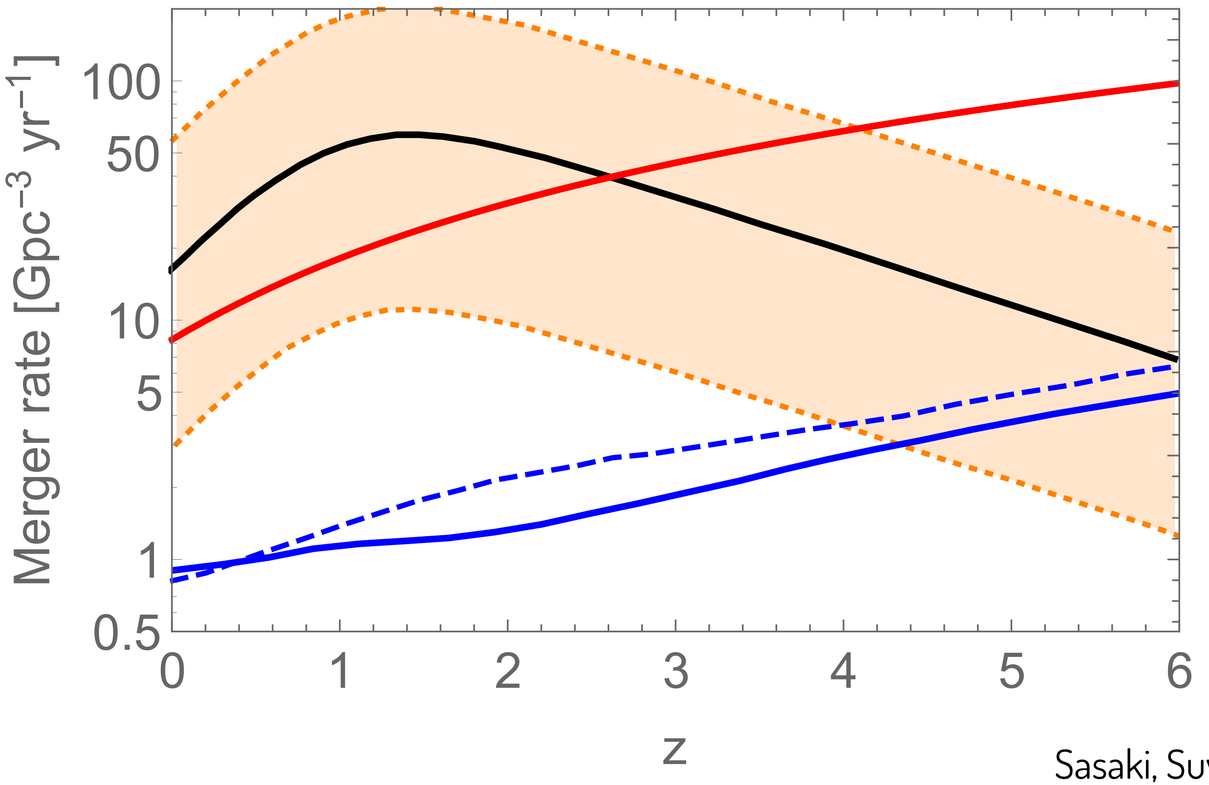
$m_1 = 0.62^{+0.46}_{-0.20} M_\odot$, $m_2 = 0.27^{+0.12}_{-0.10} M_\odot$ (Prunier+ '23)
m_2 is even lighter than NS

FAR [yr^{-1}]	Pipeline	GPS time	m_1 [$M_\odot$]	m_2 [$M_\odot$]	χ_1	χ_2	H SNR	L SNR	V SNR	Network SNR
0.20	`GstLAL`	1267725971.02	0.78	0.23	0.57	0.02	6.31	6.28	-	8.90
1.37	`MBTA`	1259157749.53	0.40	0.24	0.10	−0.05	6.57	5.31	5.81	10.25
1.56	`GstLAL`	1264750045.02	1.52	0.37	0.49	0.10	6.74	6.10	-	9.10

LVK '22

Evidence? 2

Redshift dependence



Stellar (upper limit)

Stellar (lower limit)

Stellar

PBH binaries (high z) $f_{\rm PBH}=10^{-3}$

PBH binaries (low z) $f_{\rm PBH}=1$, model A

PBH binaries (low z) $f_{\rm PBH}=1$, model B

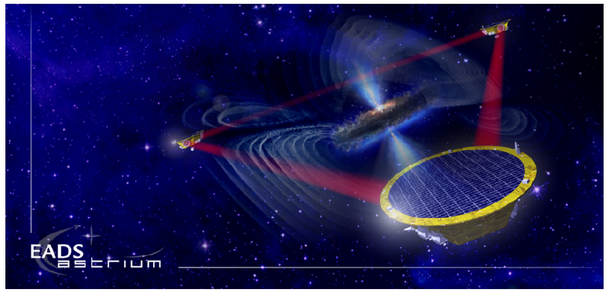
Sasaki, Suyama, Tanaka, Yokoyama '18

(indirect) Evidence? 3

$$\frac{\delta\rho}{\rho} \sim 1$$

if $M_{\rm BH} \sim 10^{20}\,{\rm g}$
→ 100% Dark Matter

induced GW b.g.



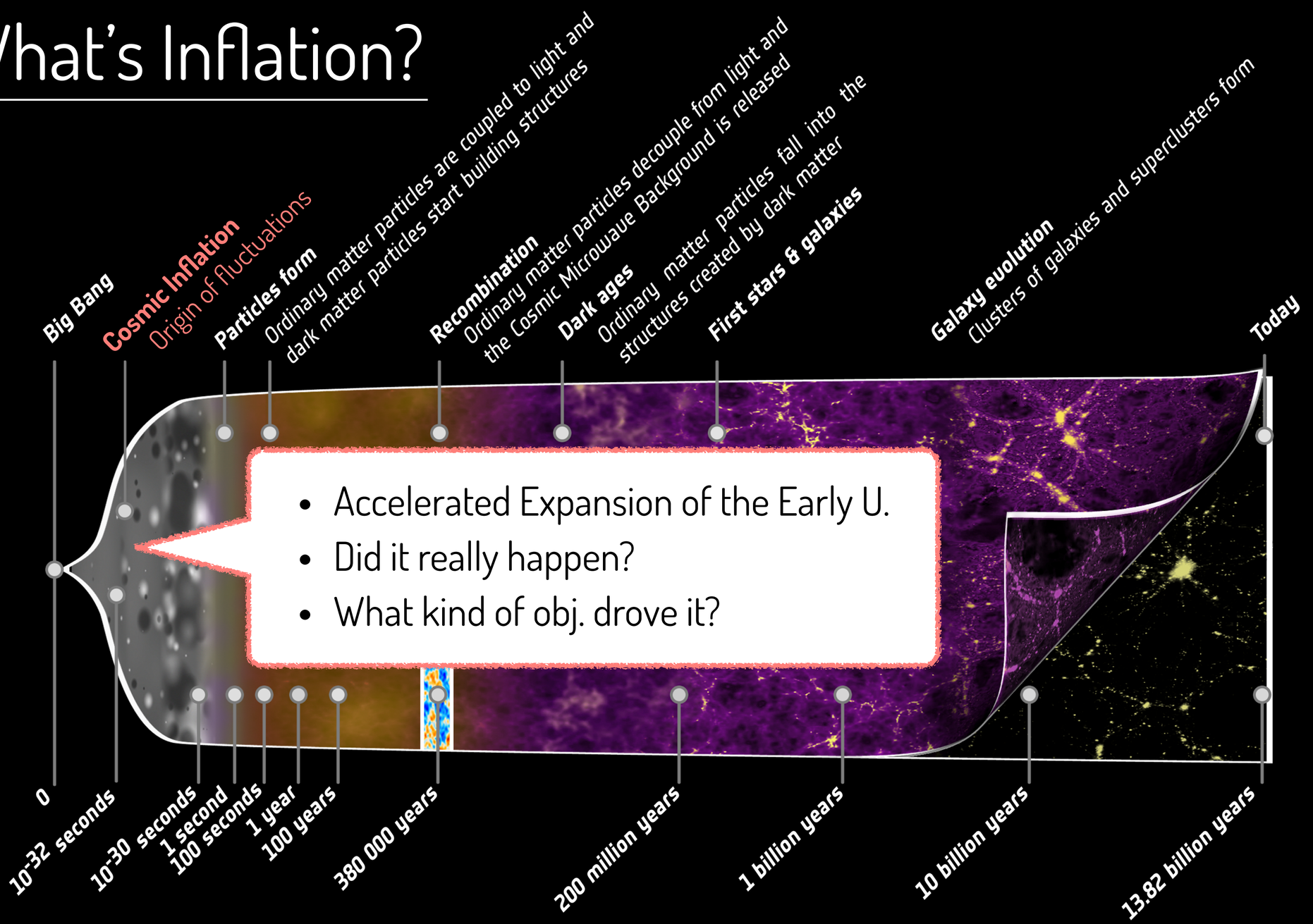
LISA

$$\mathcal{P}_\zeta \sim 10^{-2}$$

Radiation Era

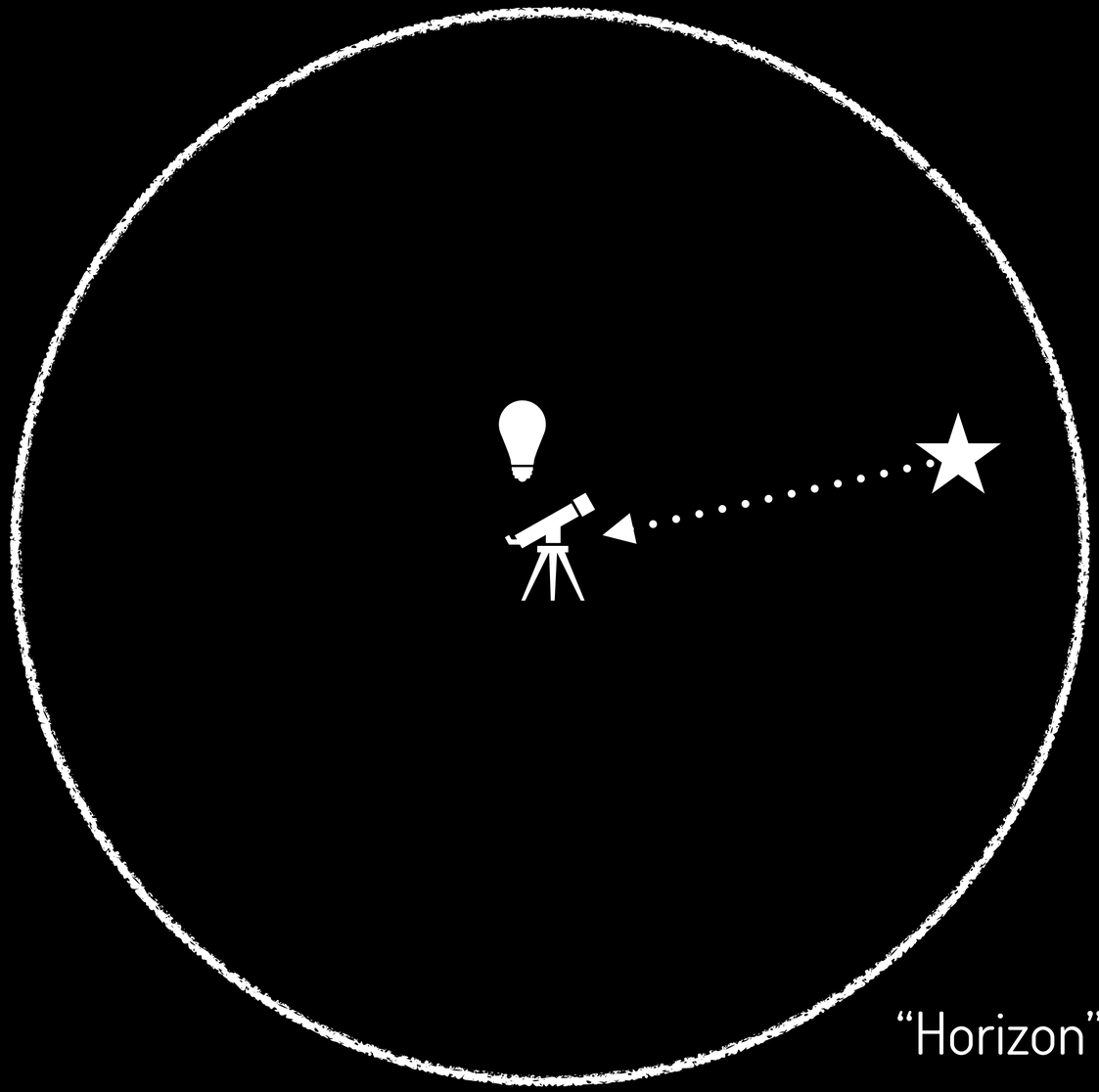
3. PBH & Inflation

What's Inflation?



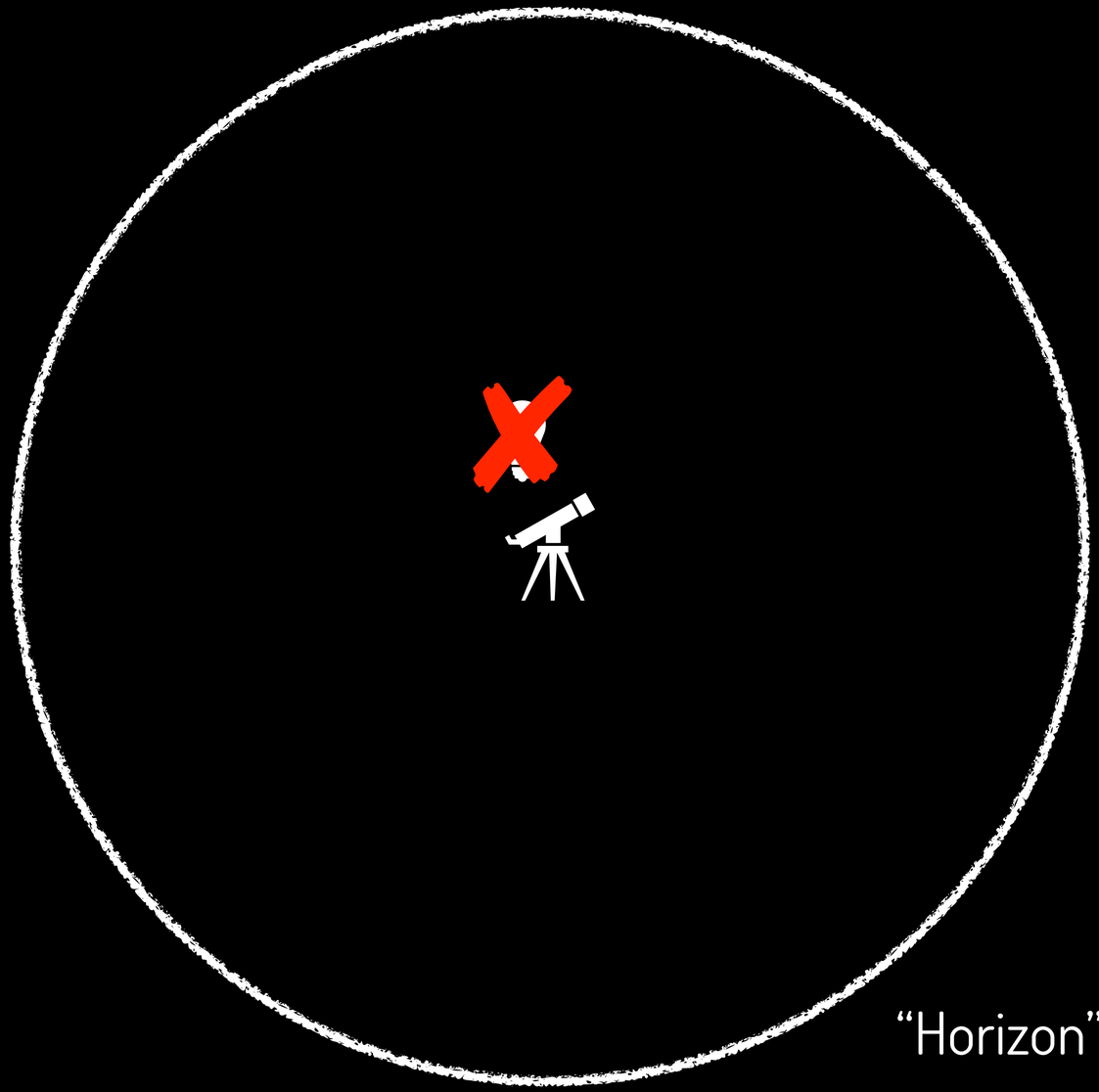
- Accelerated Expansion of the Early U.
- Did it really happen?
- What kind of obj. drove it?

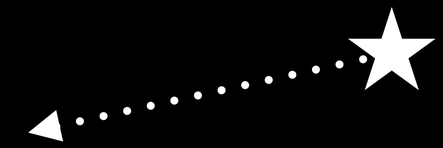
Generation of PTB



"Horizon" of the expanding U.

Generation of PTB





"Horizon" of the expanding U.

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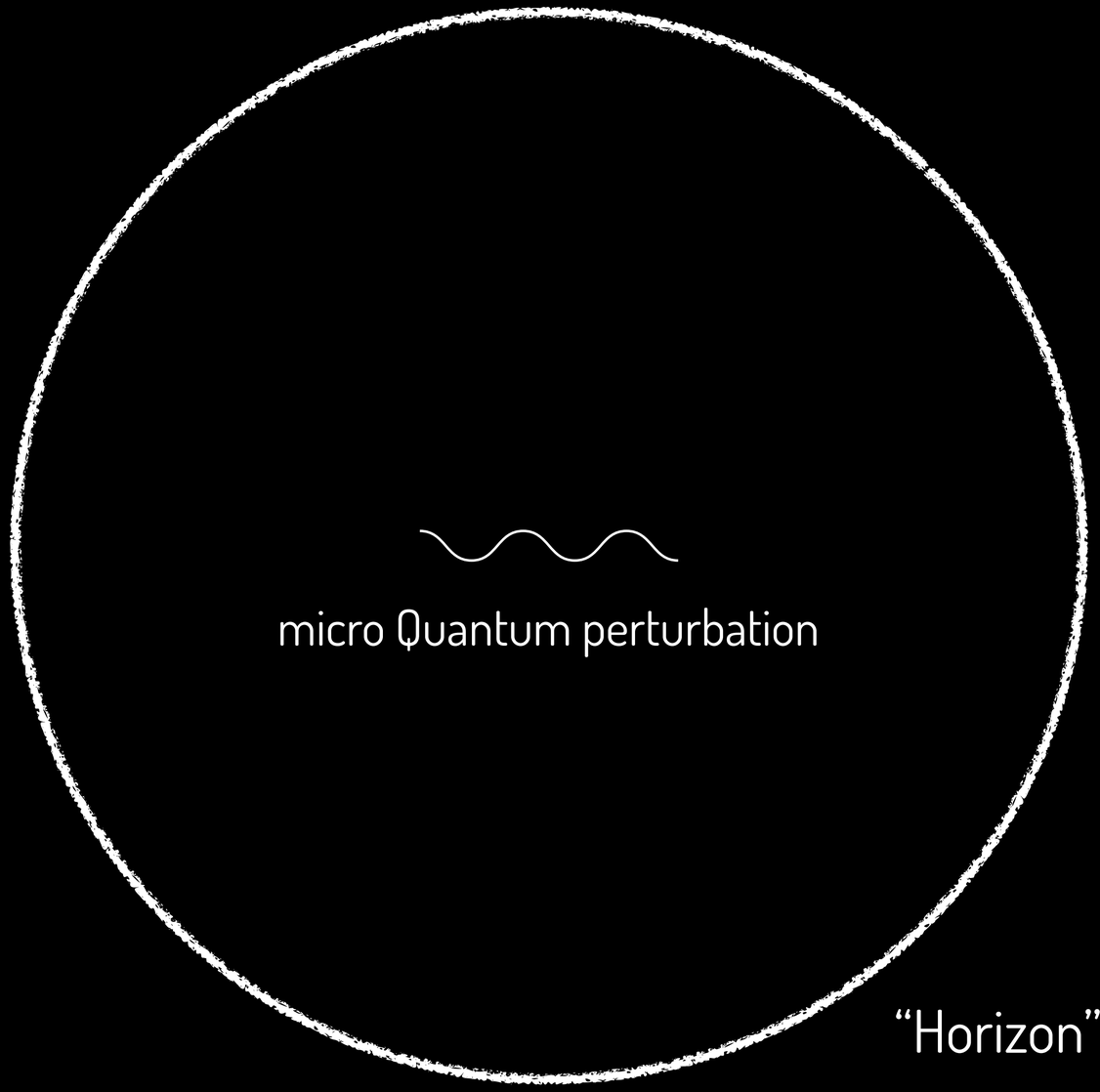
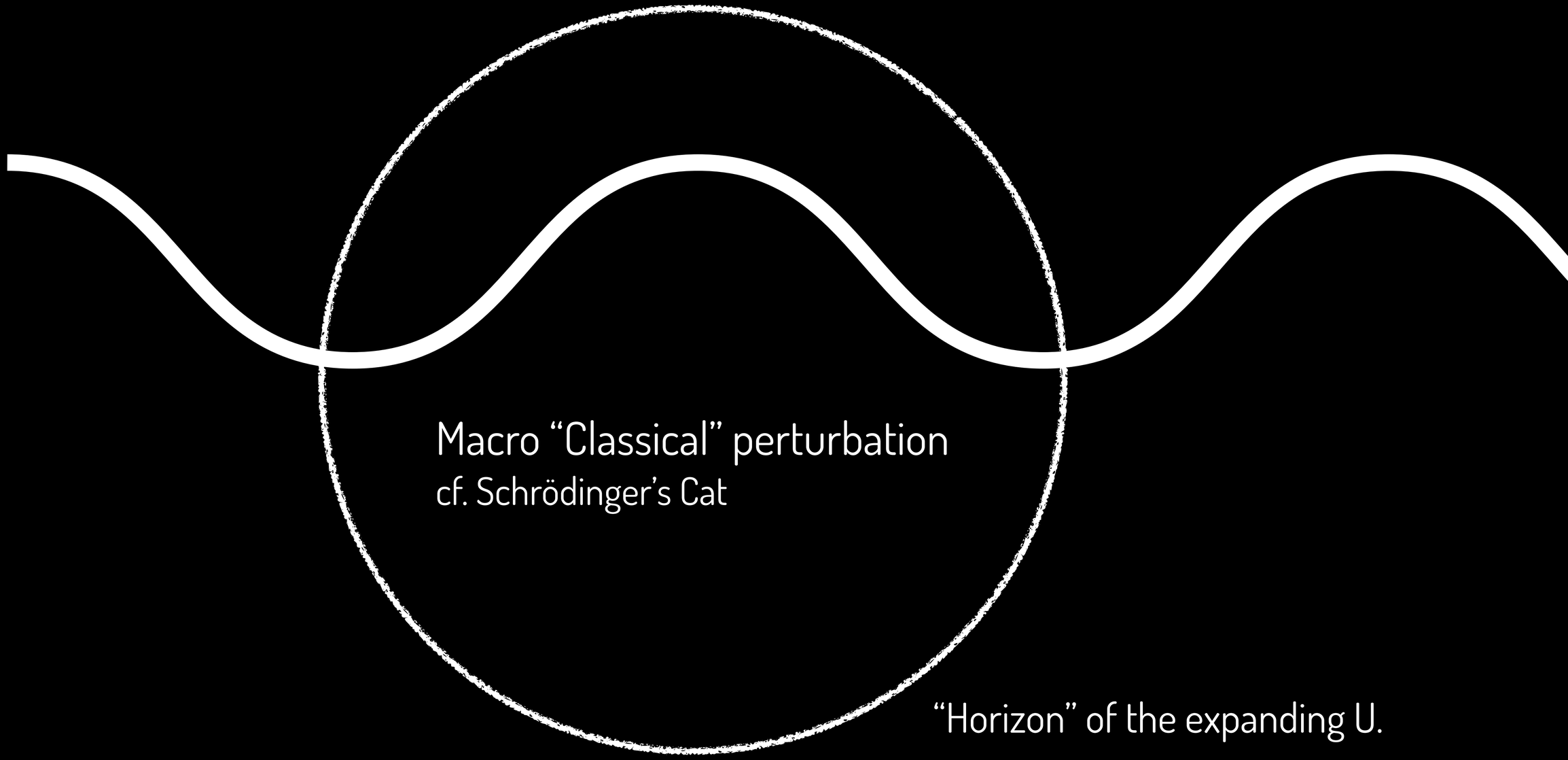
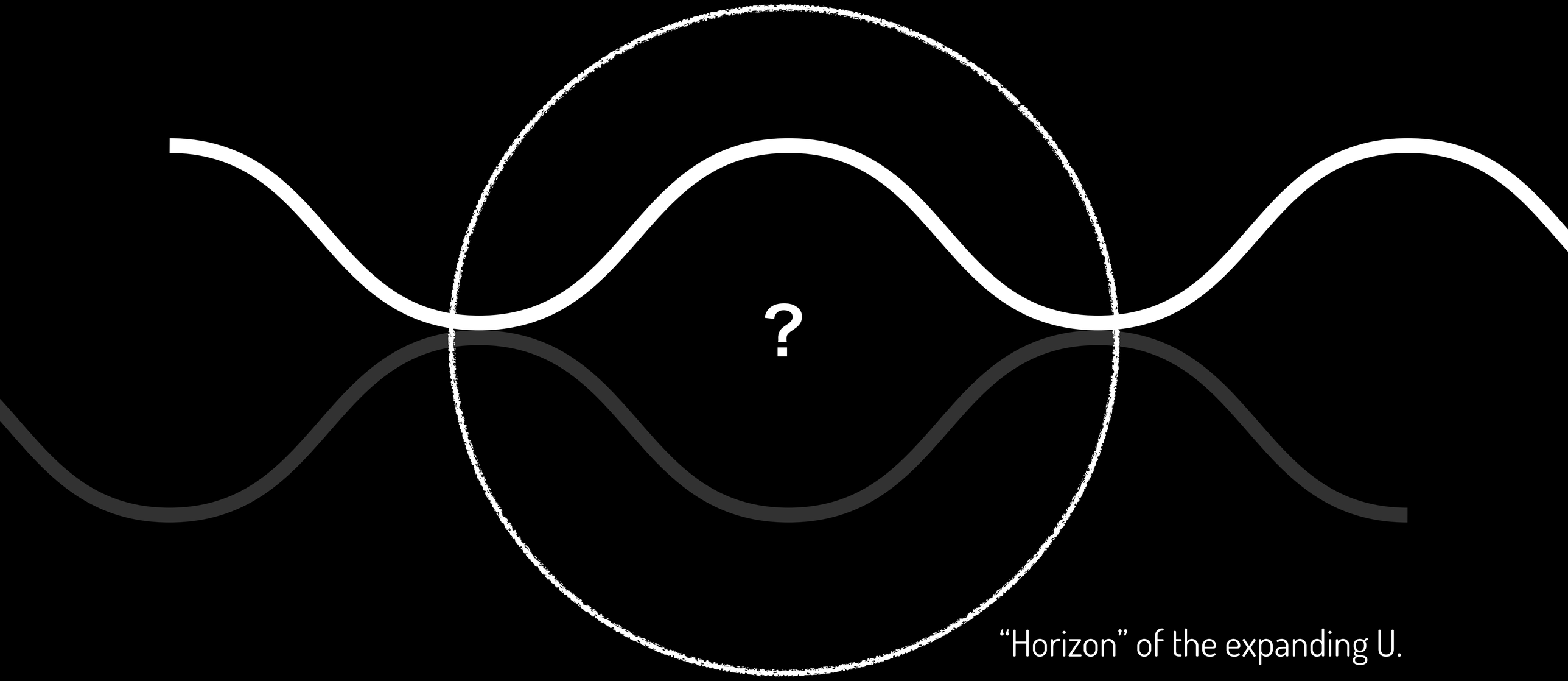


“Horizon” of the expanding U.

Generation of PTB



Generation of PTB



“Horizon” of the expanding U.

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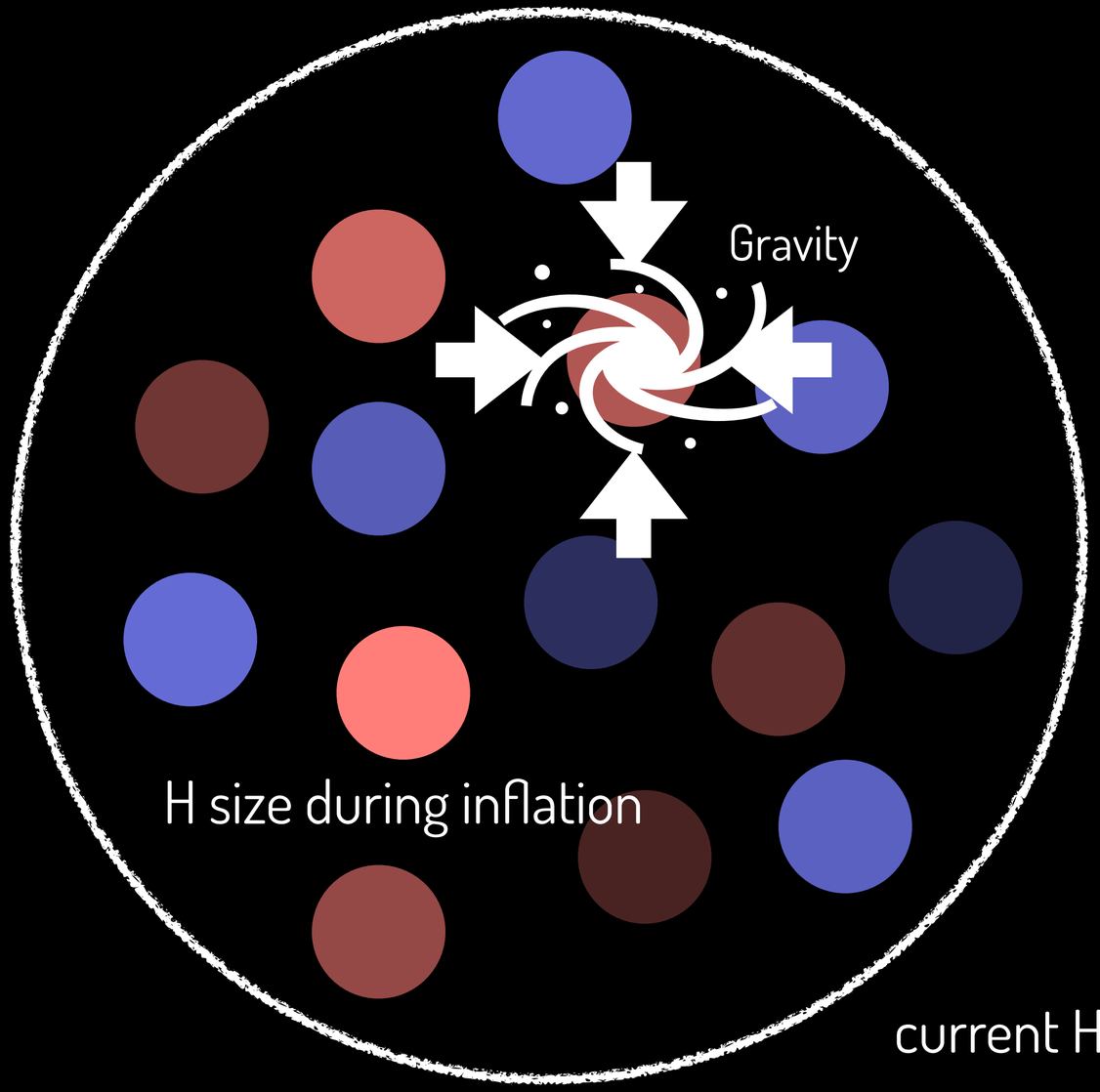
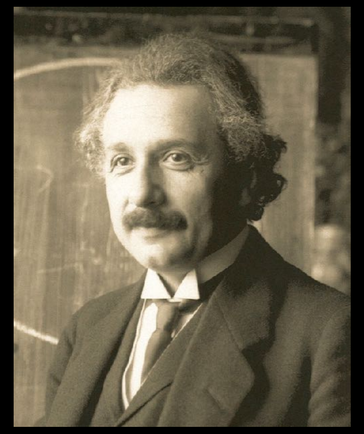
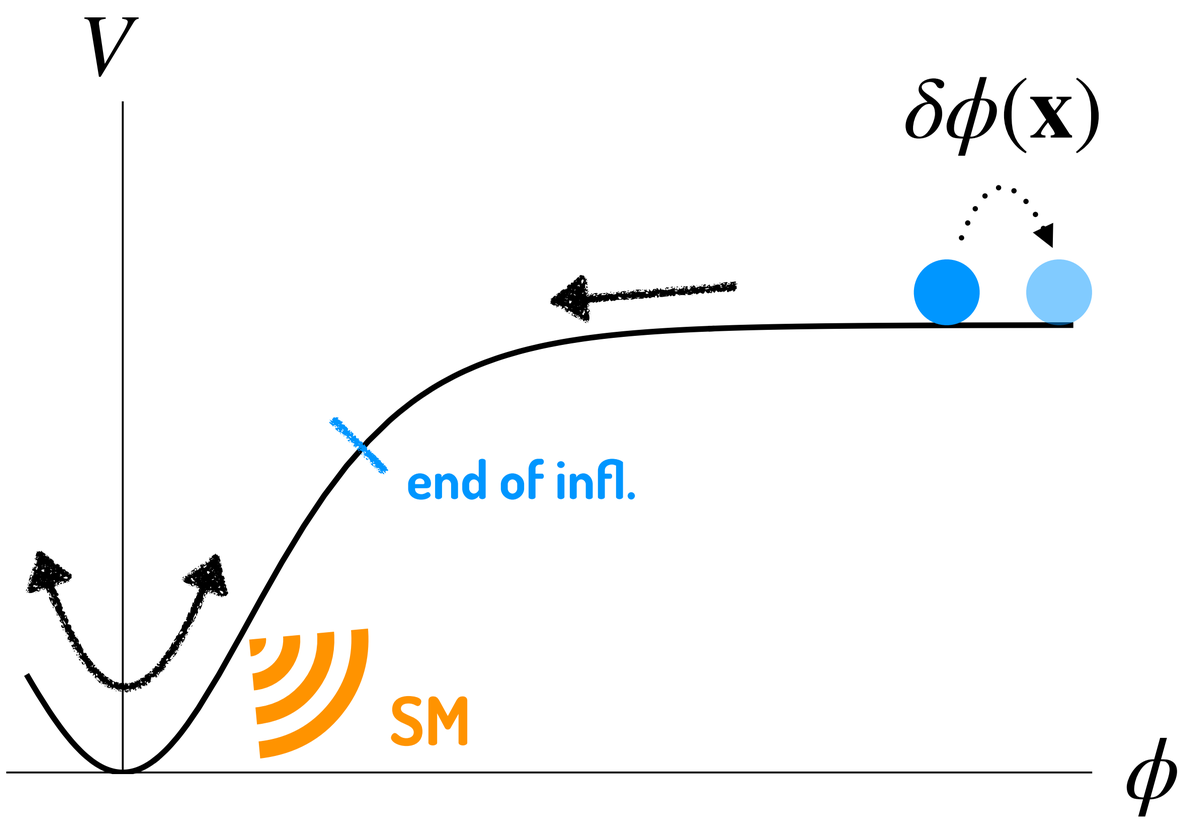




Energy = Mass

Large PTB?



Lyth, Malik, Sasaki '05

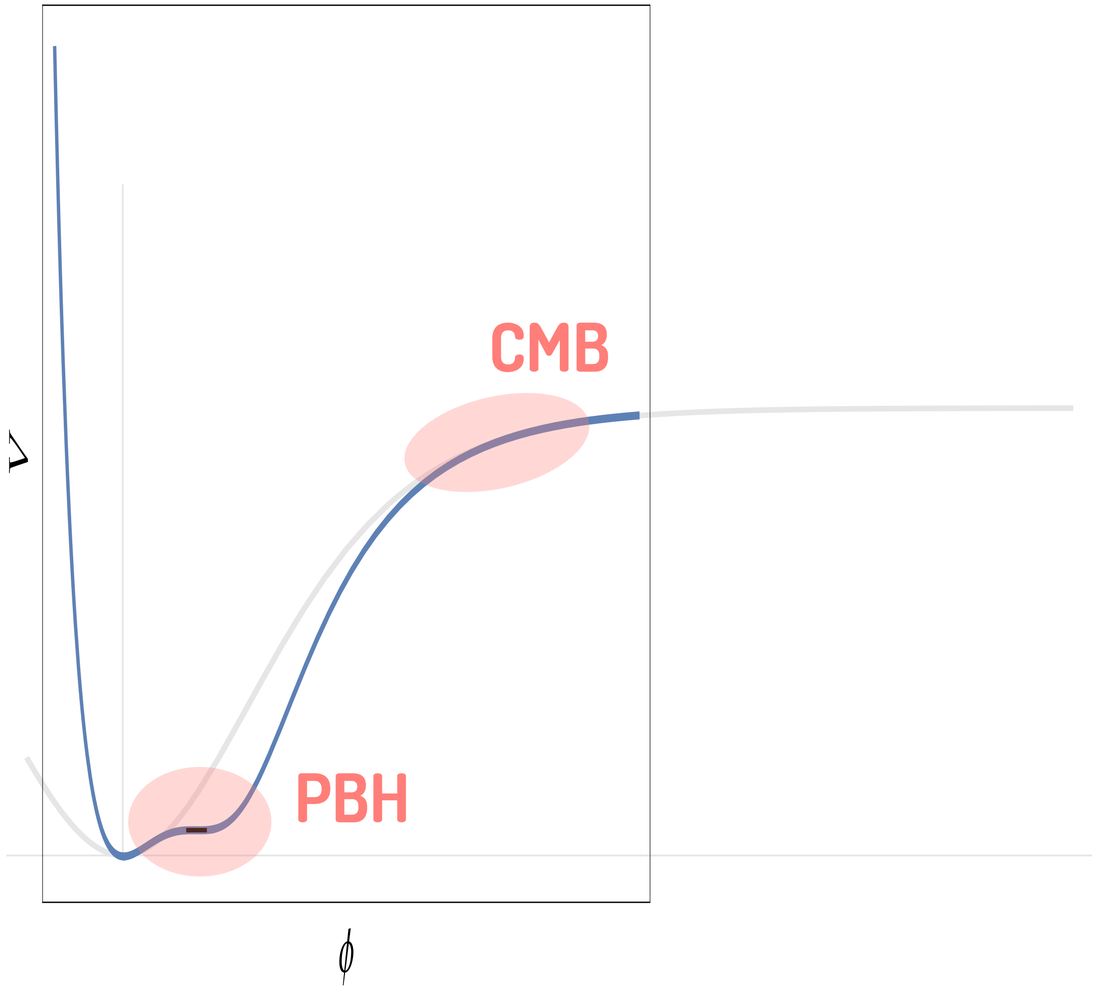
- Time shift $\delta N(\mathbf{x})$ is conserved on superH
- Equivalent to Curv. PTB $\zeta(\mathbf{x})$

e-folds: $\mathrm{d}N = H\mathrm{d}t = \dfrac{\dot{a}}{a}\mathrm{d}t$

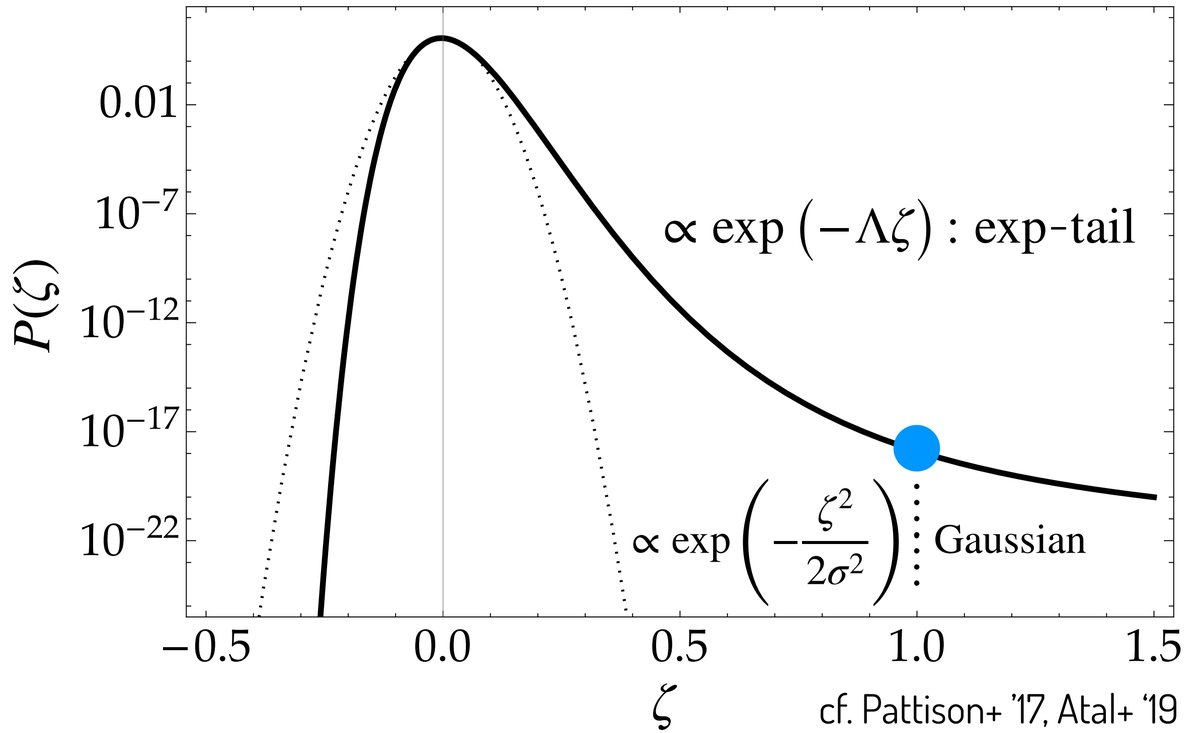
local U.: $\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{e}^{2\zeta(t,\mathbf{x})}\mathrm{d}\mathbf{x}^2$

$$\zeta(\mathbf{x}) = \delta N(\mathbf{x}) \simeq -\frac{\overline{H}}{\overline{\dot{\phi}}}\delta\phi(\mathbf{x})$$

Exp.-tail



$\dot{\phi}$ is reducing → $\delta\phi$'s effect is asymmetric!



$\delta\phi \to \zeta = \delta N$: non-linear relation

Triangle study

Universal Criterion

Atal+ '19
Escrivà, YT, Yokoyama, Yoo '22

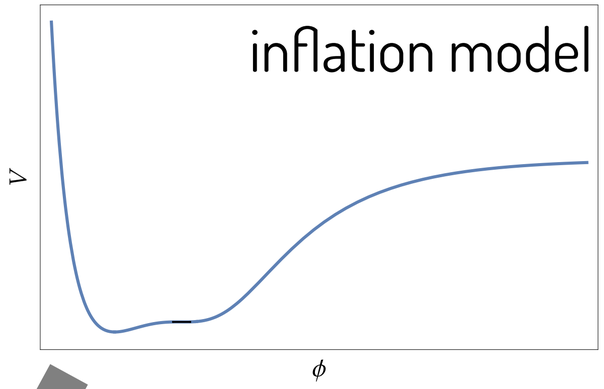
$$\mathscr{C}(r) = \frac{2}{3}\left[1 - (1 + r\zeta'(r))^2\right]$$

$$\bar{\mathscr{C}} = \frac{1}{V_{R_\mathrm{m}}}\int_0^{R_\mathrm{m}} 4\pi R^2 \mathscr{C}\,\mathrm{d}R > \bar{\mathscr{C}}_\mathrm{th} = \frac{2}{5}$$

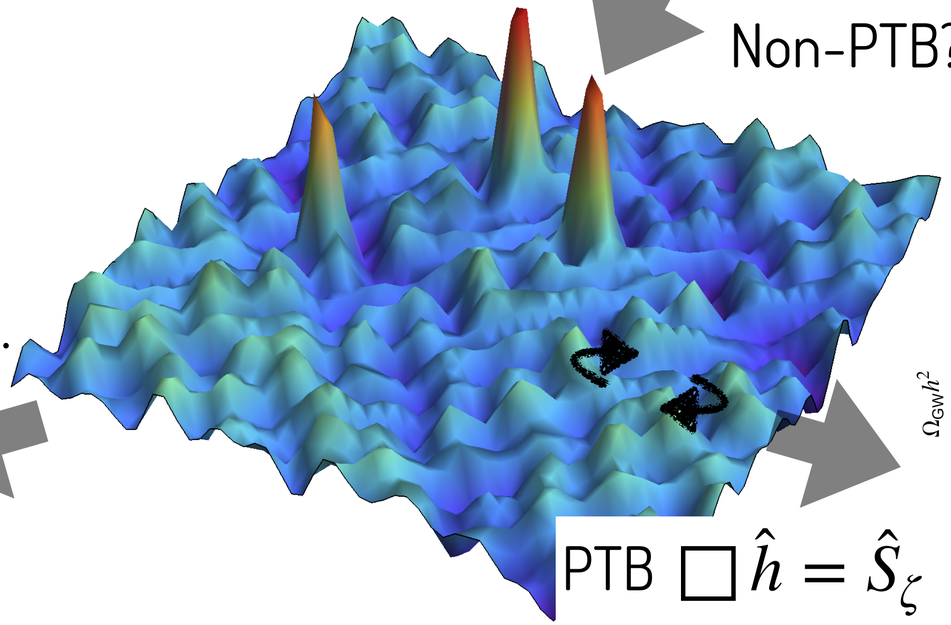
Mass Formula

Choptuik+ '93

$$M \sim M_{R_\mathrm{m}}(\bar{\mathscr{C}} - \bar{\mathscr{C}}_\mathrm{th})^{0.36}$$

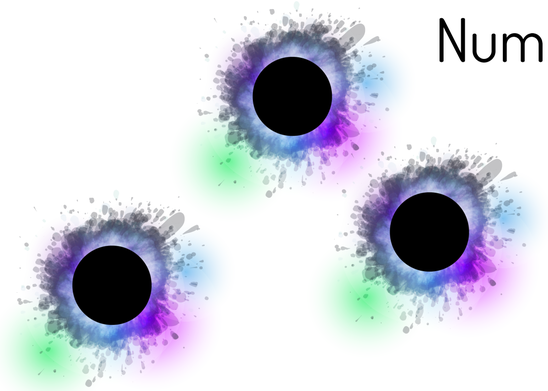


Non-PTB??



Num. Rel.

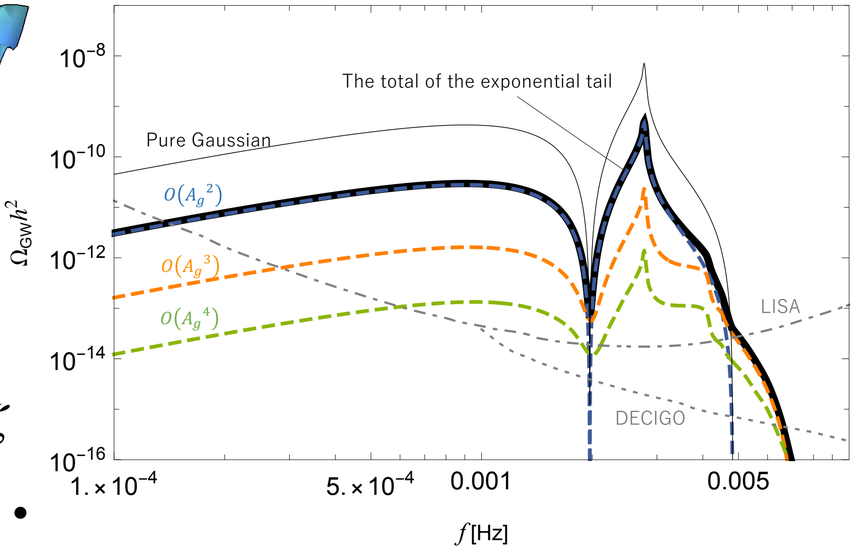
PTB $\square\hat{h} = \hat{S}_\zeta$



PBH abundance

indirect evidence

Abe, Inui, YT, Yokoyama, Yoo '22



induced GW b.g.

Stochastic Approach

Starobinsky '86

= EFT of superH fields

= Local FRLW + Correlated Brownian motion

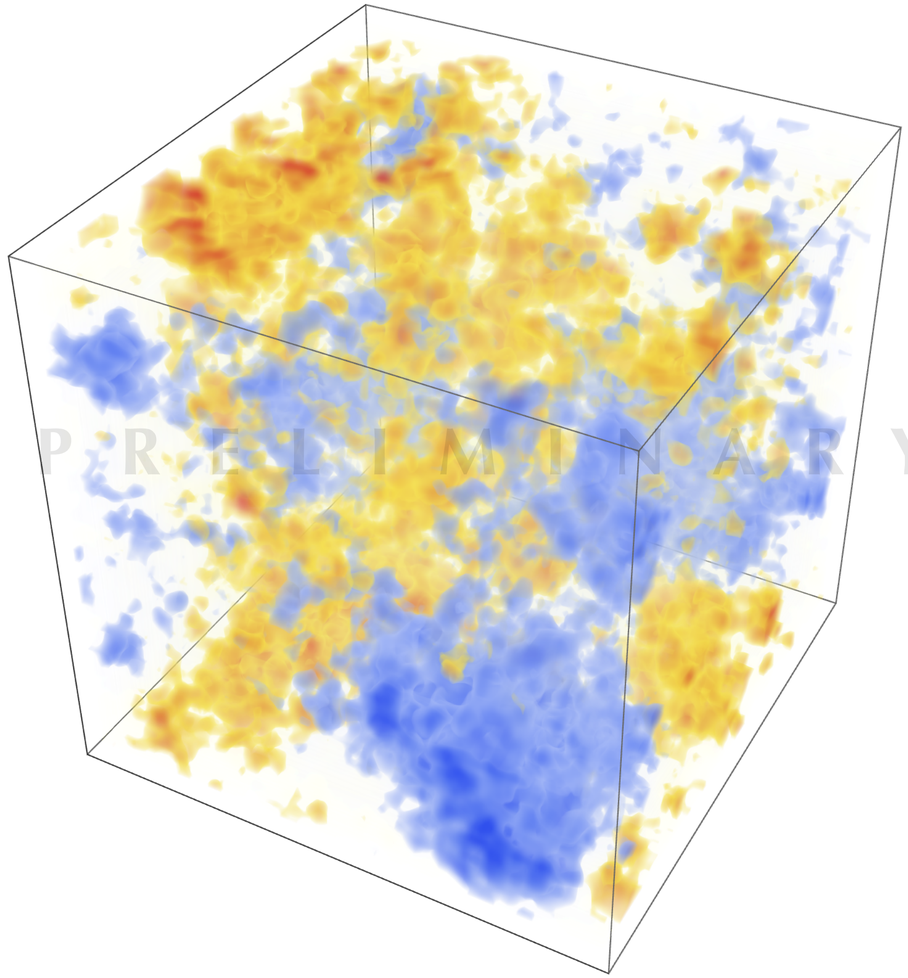
$$\approx \frac{H(N,\mathbf{x})}{2\pi}$$

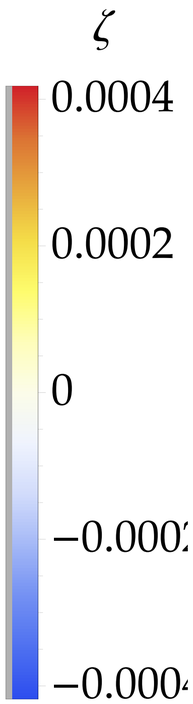
$$\begin{cases} \mathrm{d}\phi(N,\mathbf{x}) &= \dfrac{\pi(N,\mathbf{x})}{H(N,\mathbf{x})}\mathrm{d}N + \sqrt{\mathcal{P}_\phi(N,\mathbf{x})}\,\mathrm{d}W(N,\mathbf{x}), \\ \mathrm{d}\pi(N,\mathbf{x}) &= \left(-3\pi(N,\mathbf{x}) - \dfrac{V'(\phi(N,\mathbf{x}))}{H(N,\mathbf{x})}\right)\mathrm{d}N, \\ 3M_{\rm Pl}^2H^2(N,\mathbf{x}) &= \dfrac{1}{2}\pi^2(N,\mathbf{x}) + V(\phi(N,\mathbf{x})), \\ \mathrm{d}W(N,\mathbf{x})\mathrm{d}W(N',\mathbf{y}) &= \dfrac{\sin k_\sigma(N)\,|\mathbf{x}-\mathbf{y}|}{k_\sigma(N)\,|\mathbf{x}-\mathbf{y}|}\delta_{NN'}\mathrm{d}N \end{cases}$$

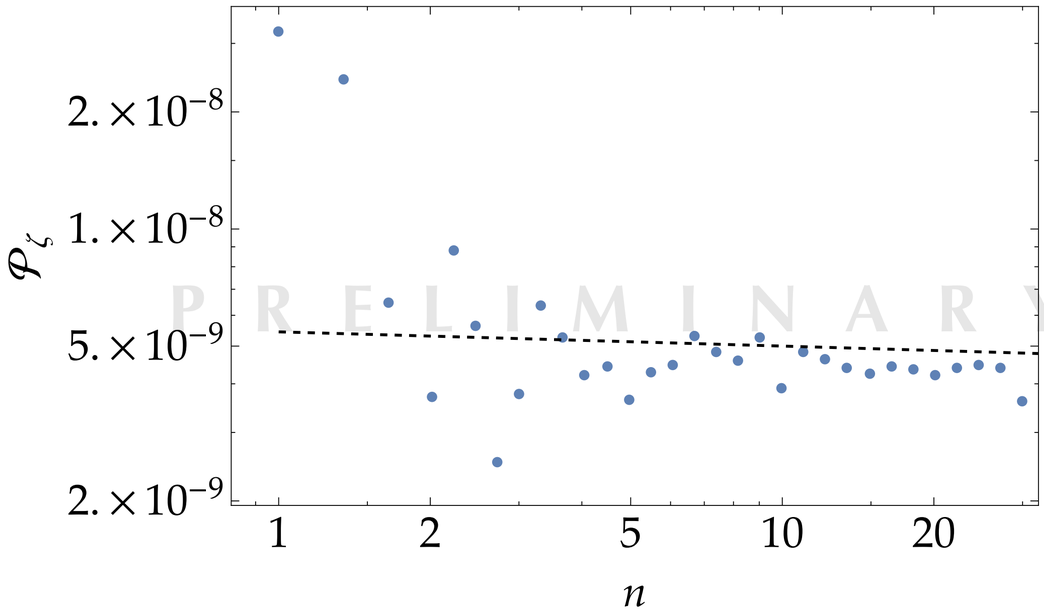
STOLAS

Mizuguchi, Murata, YT in prep.

Ex. 1: Chaotic $V = \frac{1}{2}m^2\phi^2$





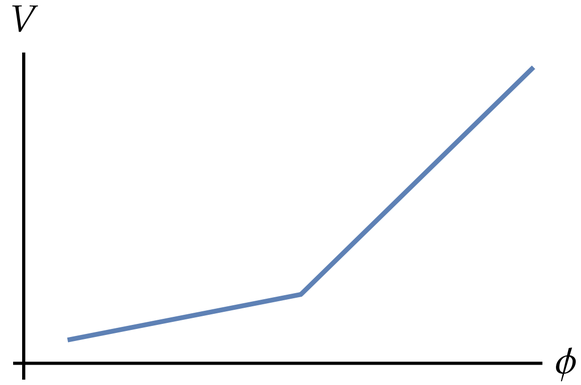


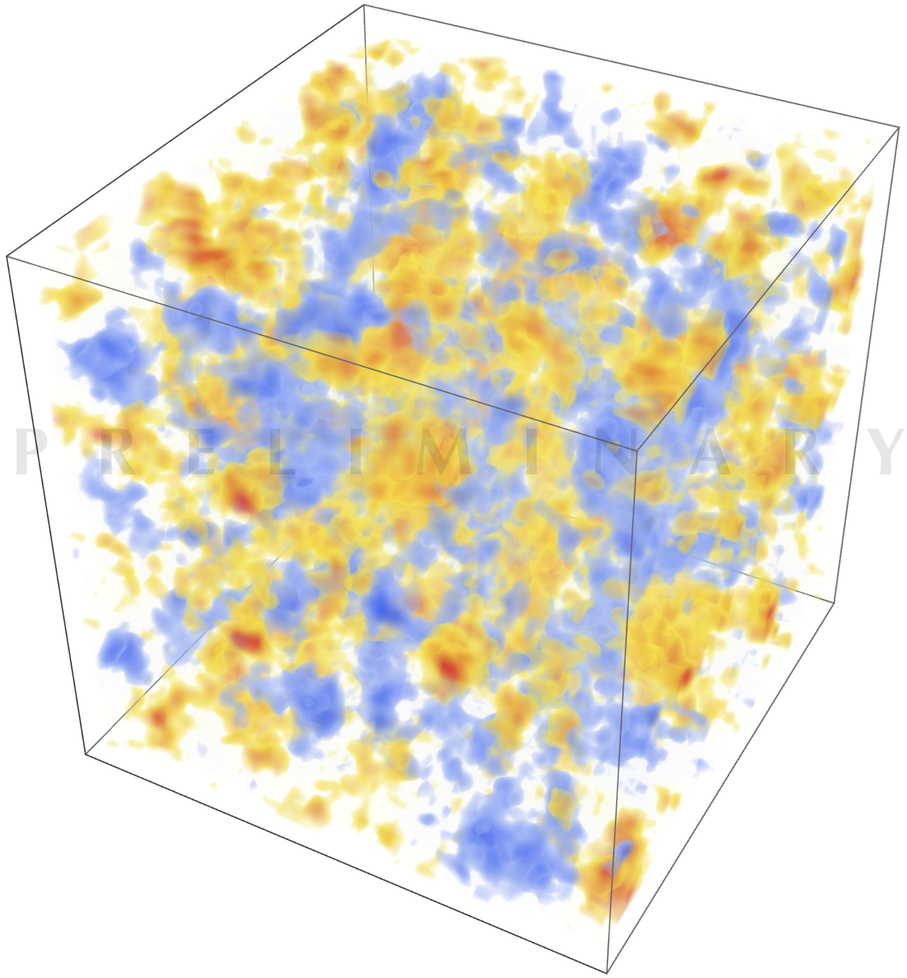
STOLAS

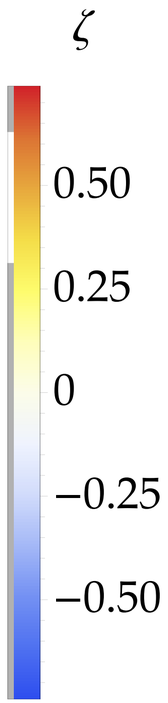
Mizuguchi, Murata, YT in prep.

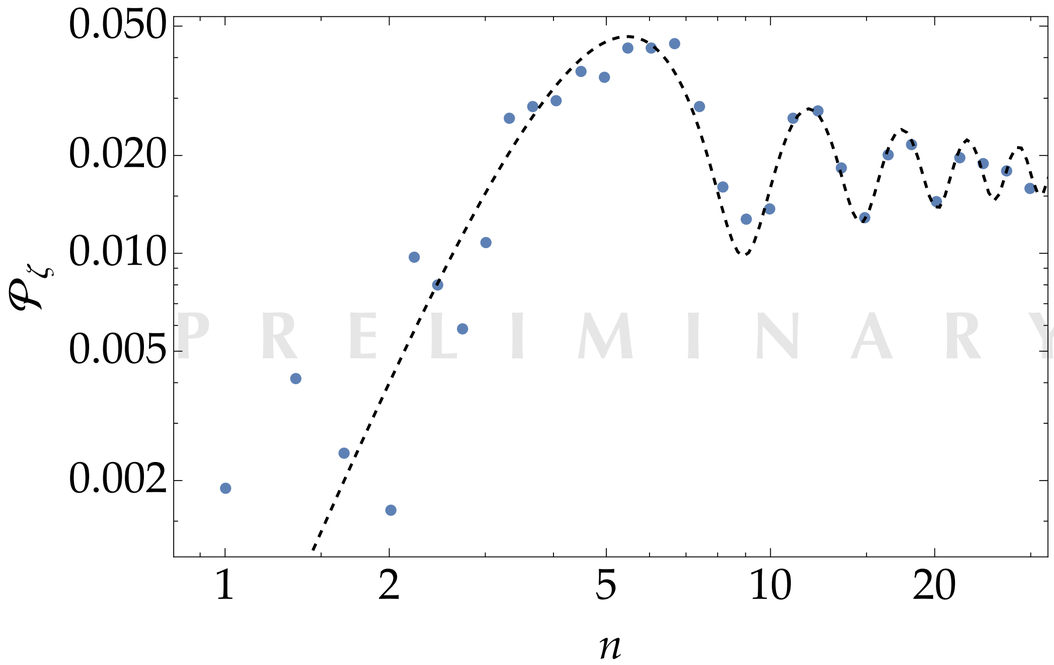
Ex. 2: Starobinsky's linear

Starobinsky '92

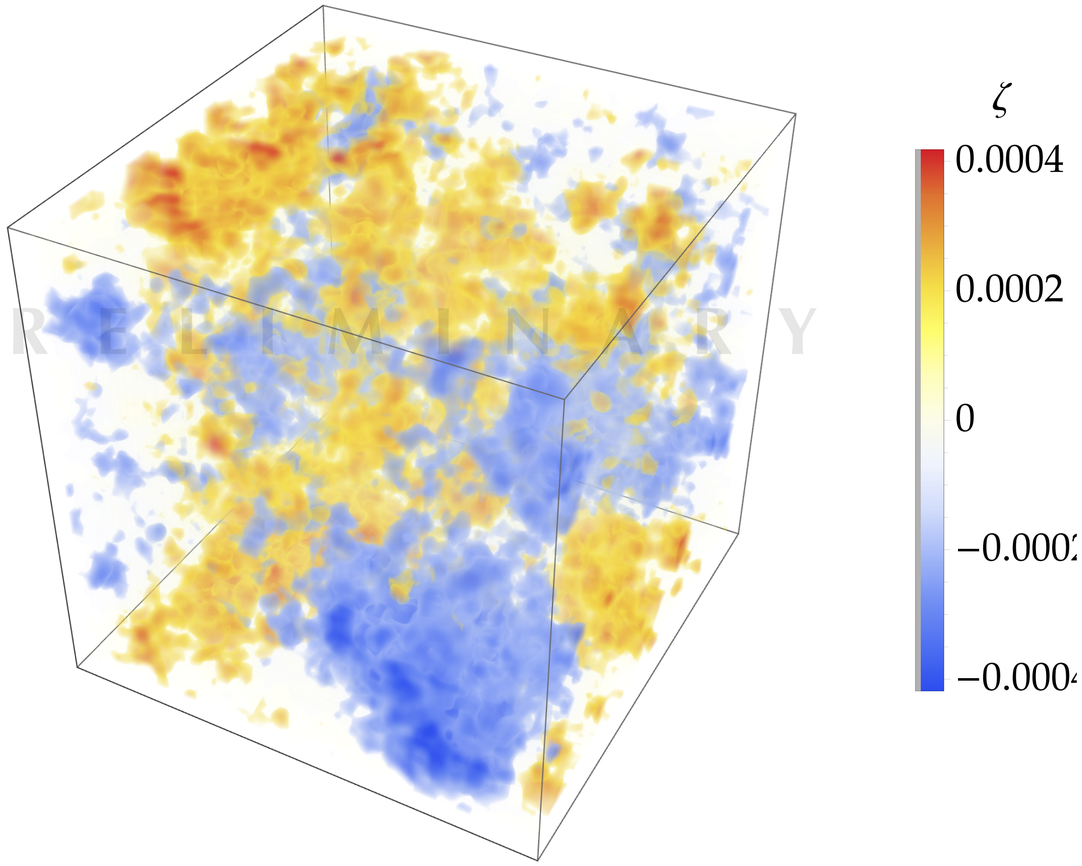




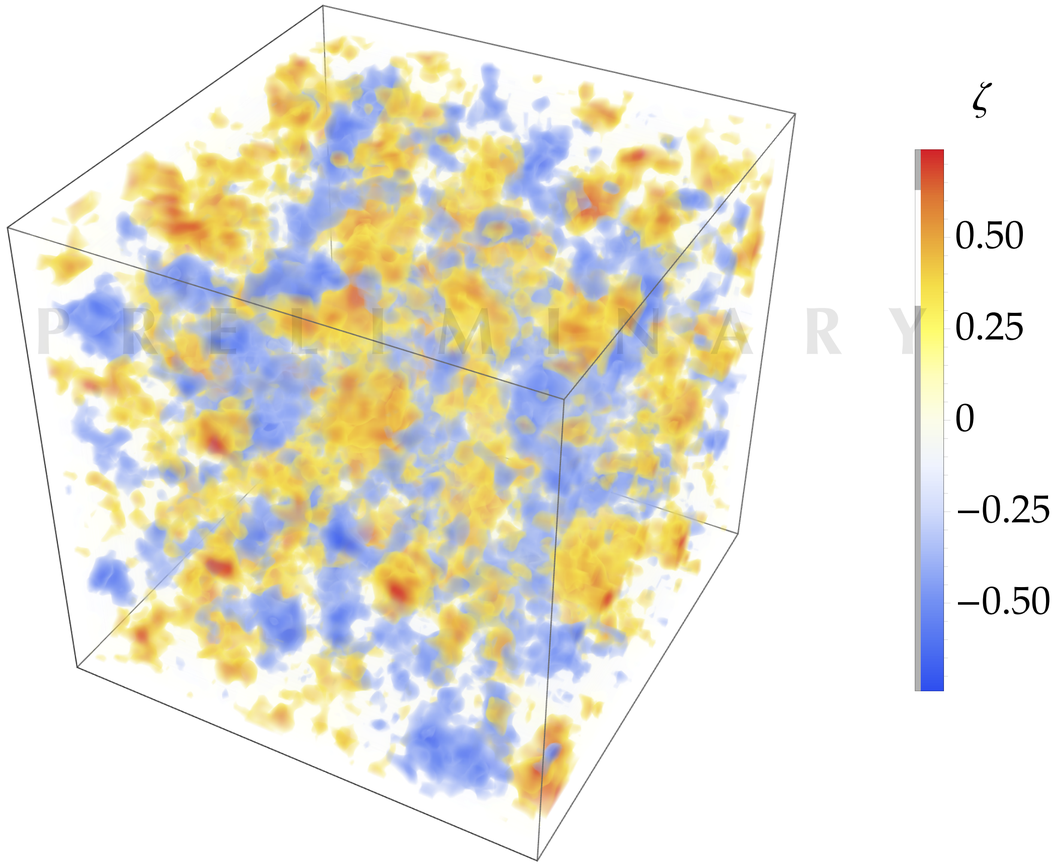




Ex. 1 : Chaotic



Ex. 2 : Starobinsky's linear

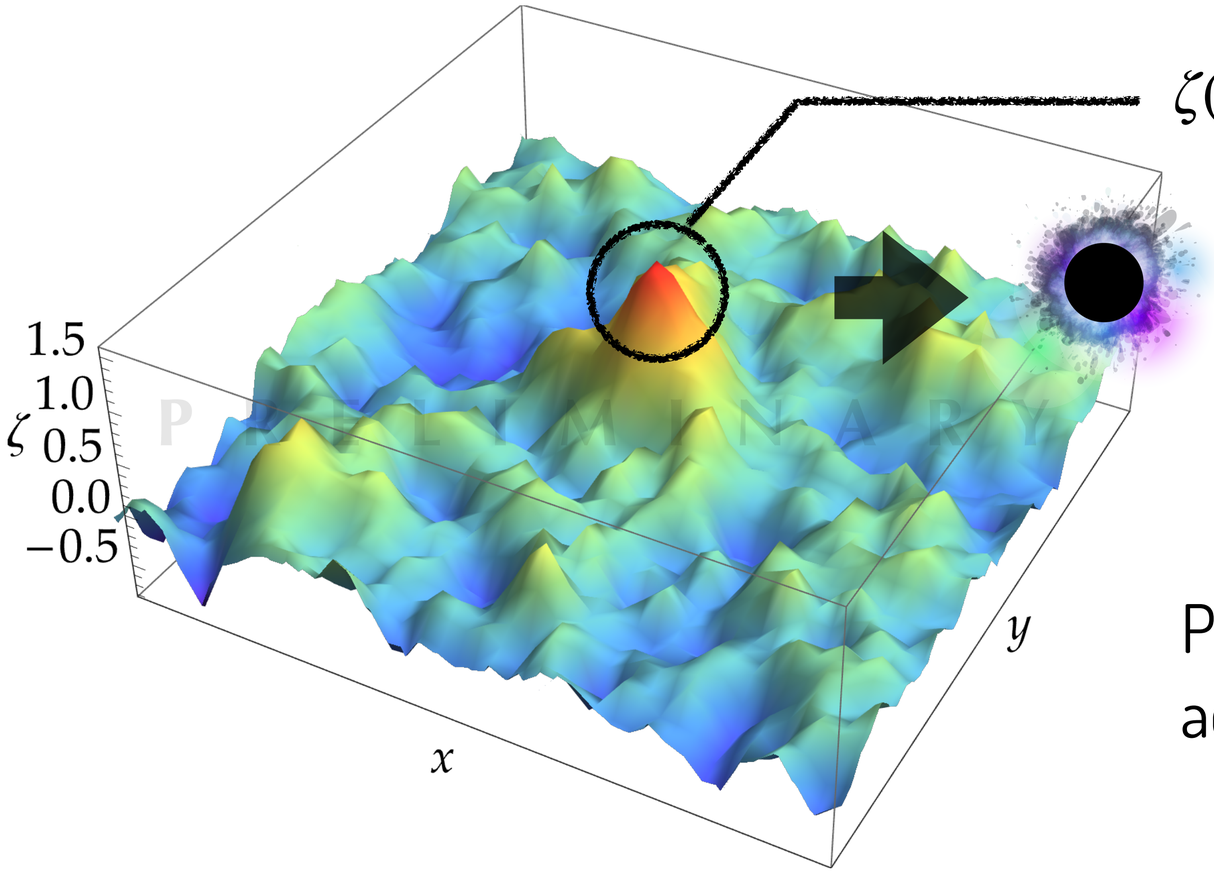


Importance Sampling

see, e.g., Jackson+ '22

Intentionally large noise @ $N = 4$

Ex. 2 : Starobinsky's linear



$$\zeta(r) \to \mathscr{C}(r) \to \bar{\mathscr{C}}_{\rm m} = 0.56 > \bar{\mathscr{C}}_{\rm th} = \frac{2}{5}$$

Probability is re-weighted
according to the probability of large noise!!

Triangle study

Universal Criterion

Atal+ '19
Escrivà, YT, Yokoyama, Yoo '22

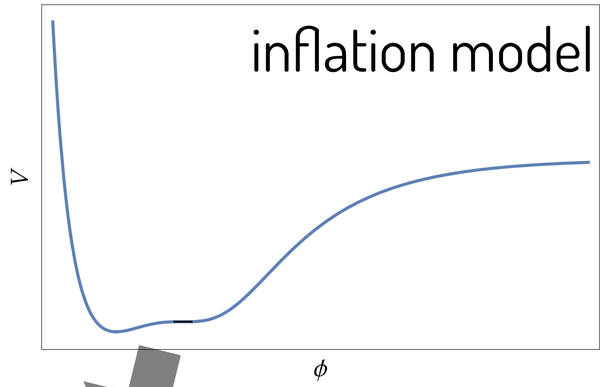
$$\mathscr{C}(r) = \frac{2}{3}\left[1 - (1 + r\zeta'(r))^2\right]$$

$$\bar{\mathscr{C}} = \frac{1}{V_{R_\mathrm{m}}}\int_0^{R_\mathrm{m}} 4\pi R^2 \mathscr{C}\,\mathrm{d}R > \bar{\mathscr{C}}_\mathrm{th} = \frac{2}{5}$$

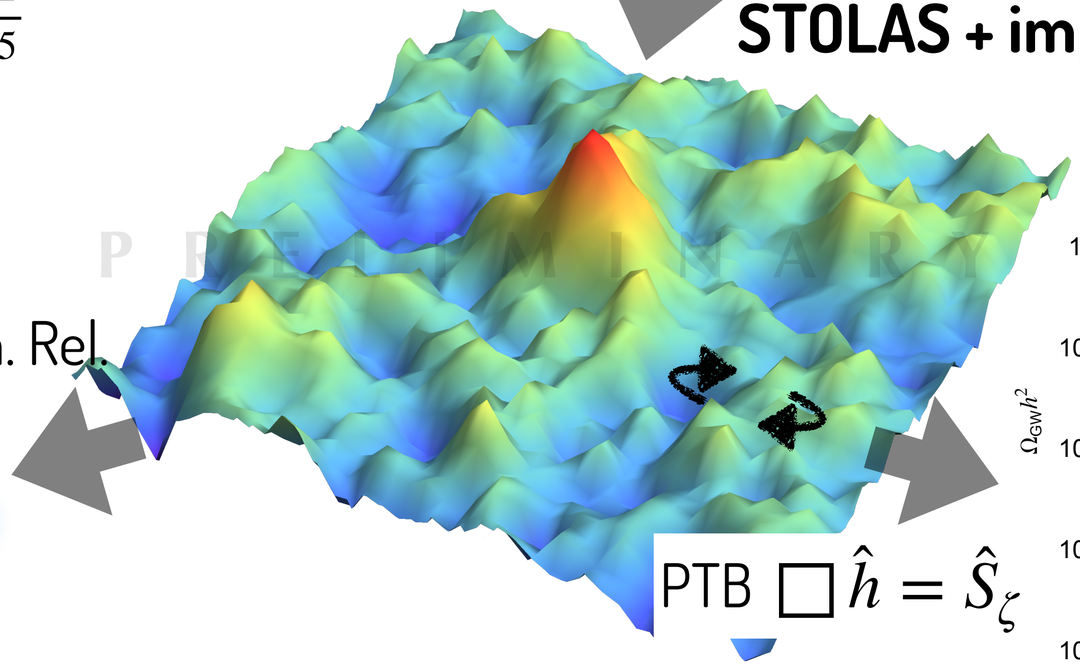
Mass Formula

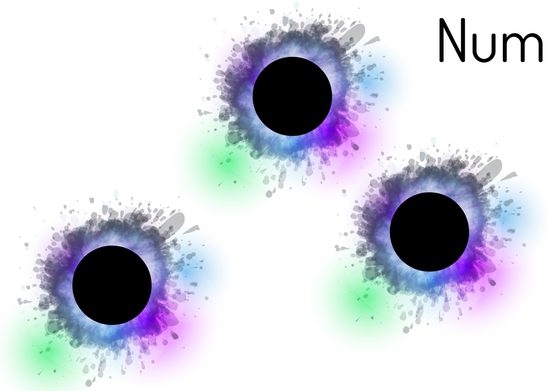
Choptuik+ '93

$$M \sim M_{R_\mathrm{m}}(\bar{\mathscr{C}} - \bar{\mathscr{C}}_\mathrm{th})^{0.36}$$



STOLAS + importance sampling





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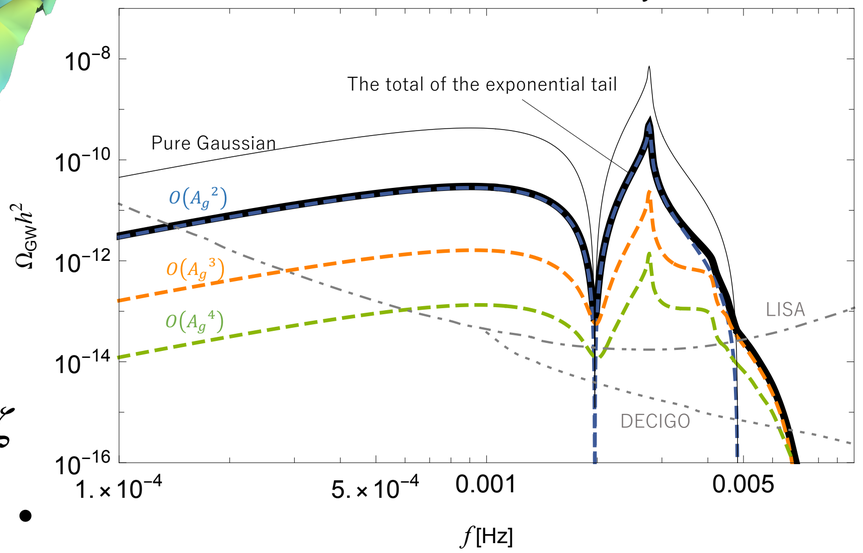


induced GW b.g.

4. Recent Topics

Pulsar Timing Array

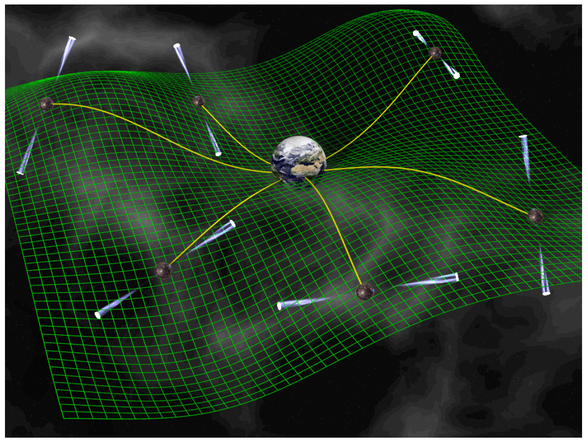
Draft version June 29, 2023
Typeset using LaTeX **twocolumn** style in AASTeX63

Tensorial PTB

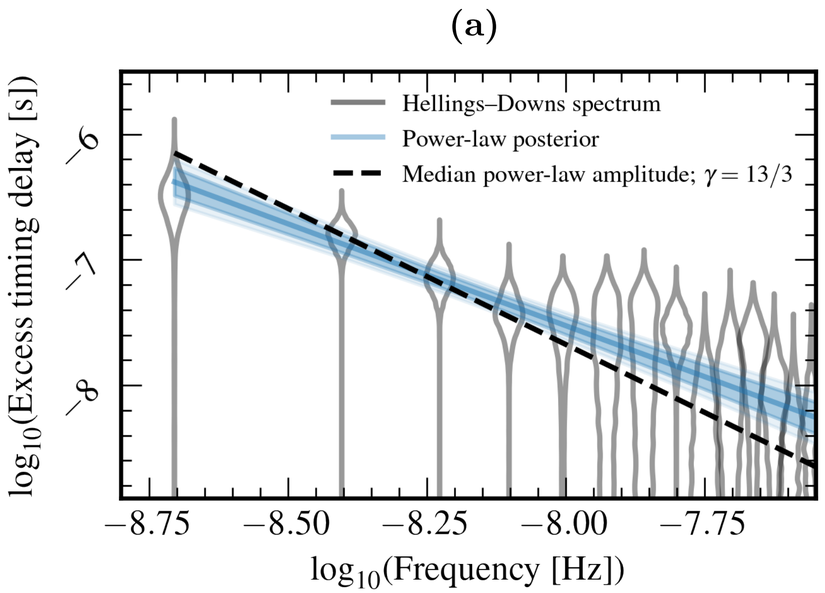
2306.16213

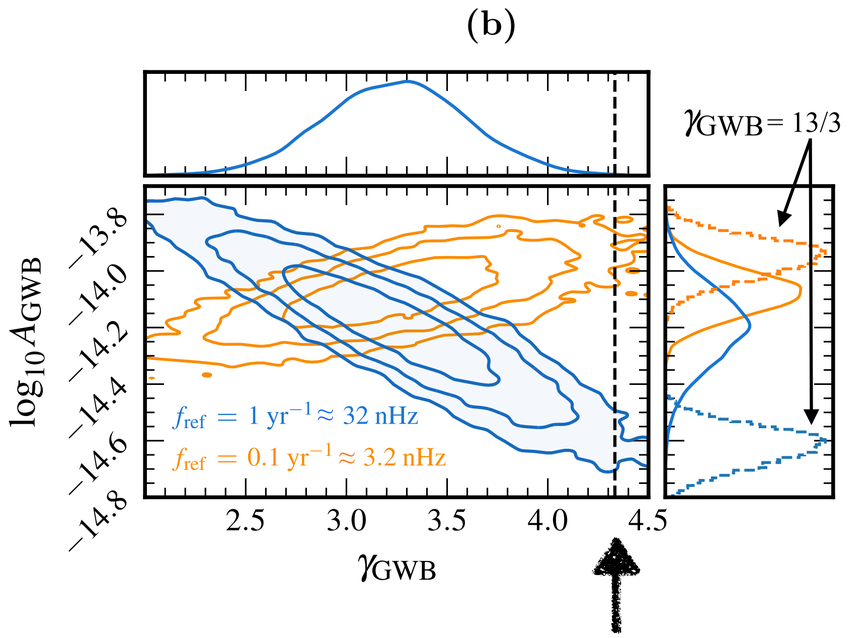
The NANOGrav 15-year Data Set: Evidence for a Gravitational-Wave Background

cf. European, Parkes (Australia), Chinese



$\sim$ nHz ($\sim$ yr^{-1}) GW b.g.





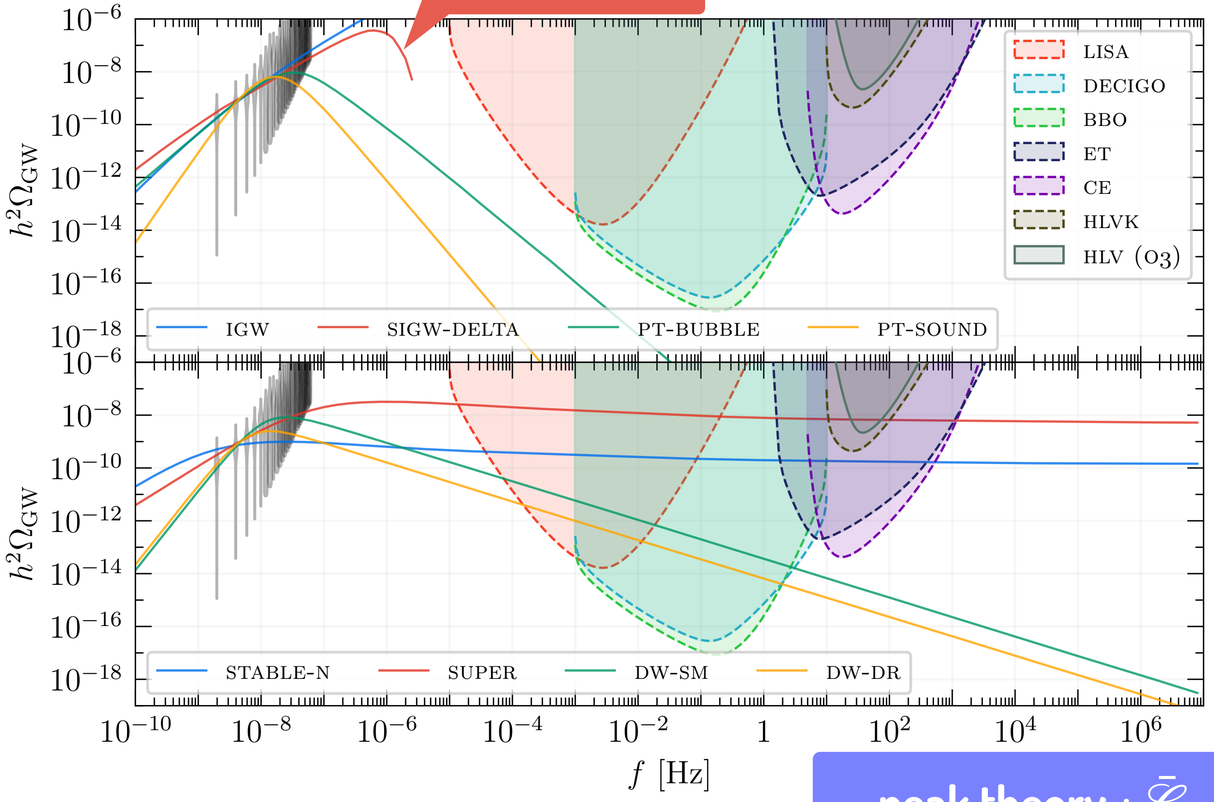
Supermassive BH binary

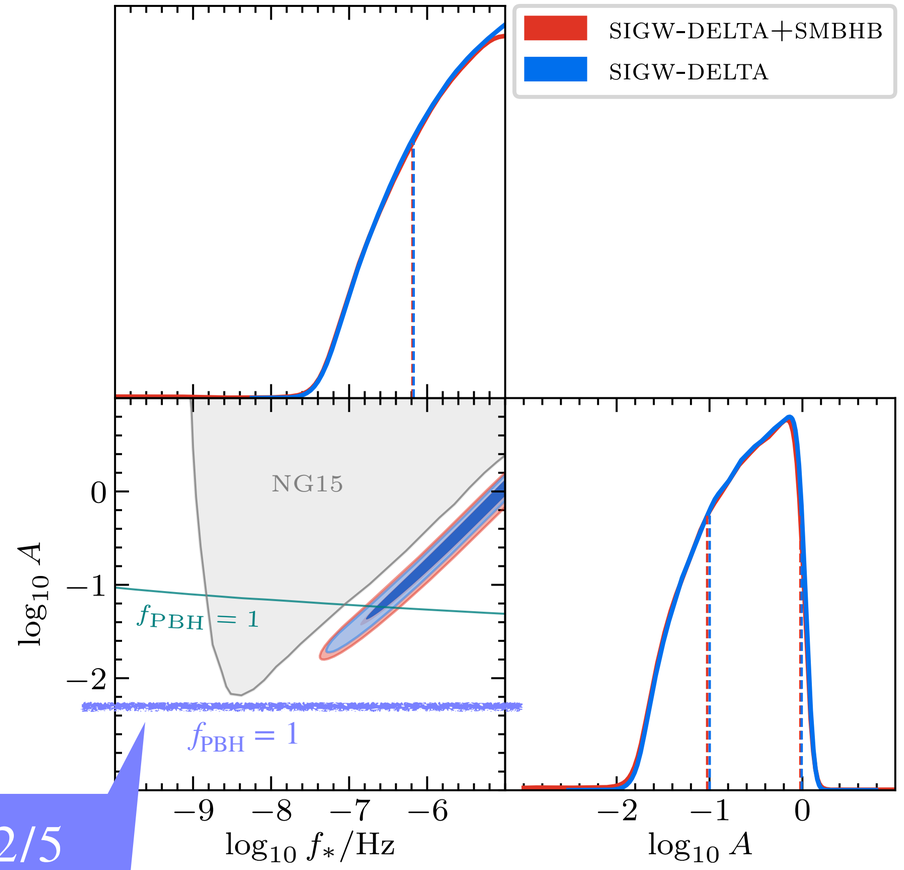
Pulsar Timing Array

2306.16219

The NANOGrav 15-year Data Set: Search for Signals from New Physics

induced GWs





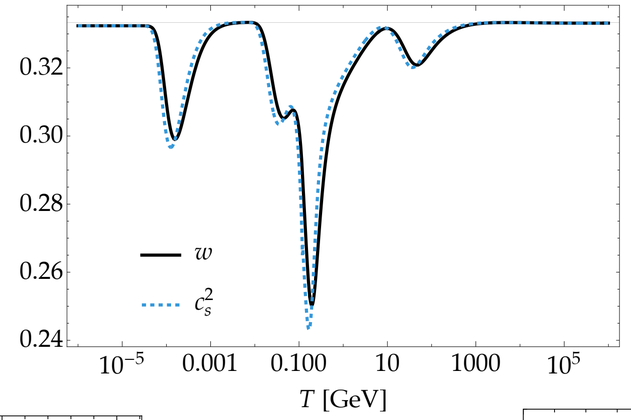
peak theory + $\bar{\mathscr{C}}_{\rm th} = 2/5$
(cf. Kitajima, YT, Yokoyama, Yoo '21)

Pulsar Timing Array

QCD effect $f \sim \mathrm{nHz} \leftrightarrow T \sim 100\,\mathrm{MeV}$

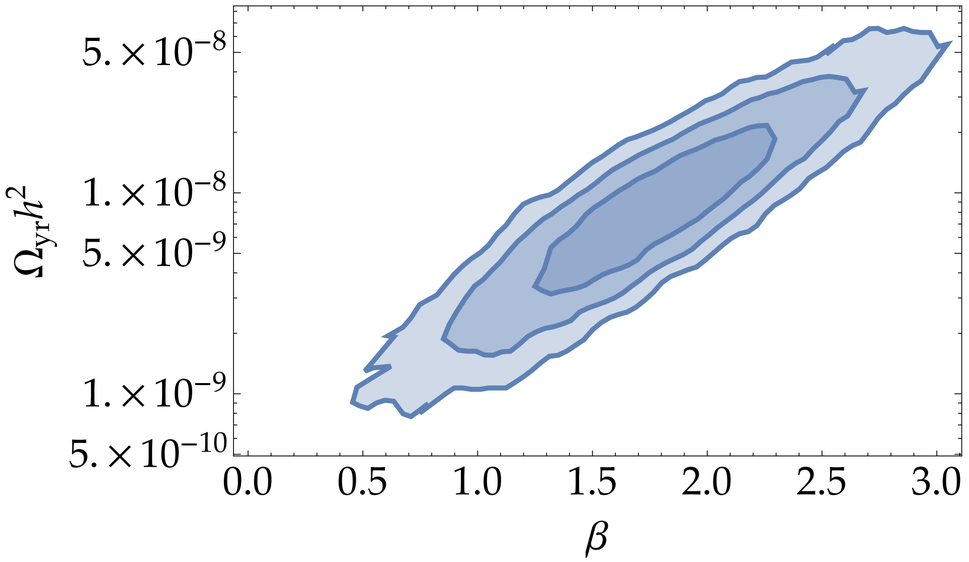
Abe, YT, Ueda '20, Abe, YT '23
cf. EPTA '23

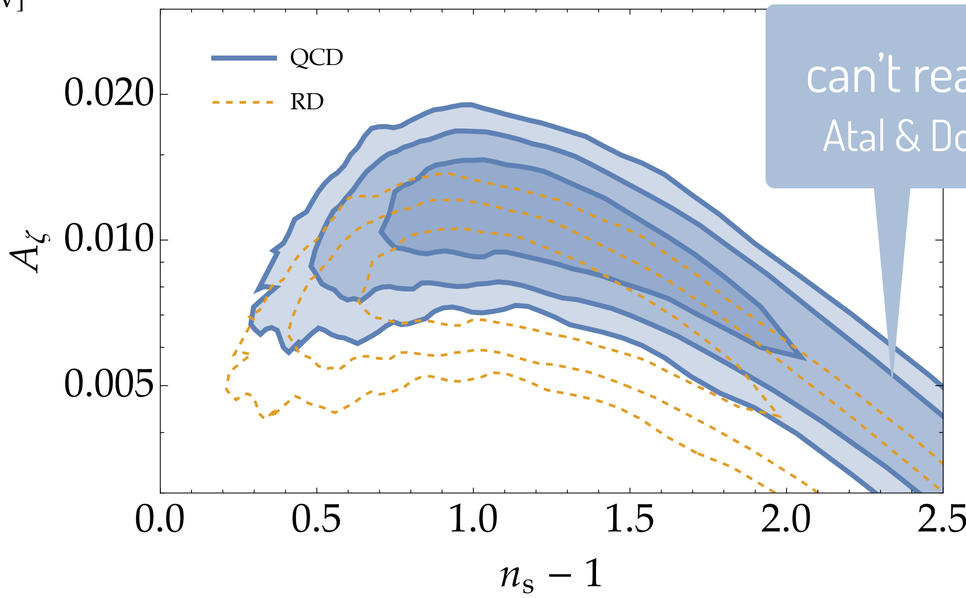
$$\Omega_{\rm GW} = \Omega_{\rm yr}\left(\frac{f}{f_{\rm yr^{-1}}}\right)^{\beta}$$



$$\mathcal{P}_\zeta = A_\zeta\left(\frac{k}{k_{\rm yr^{-1}}}\right)\Theta(k_{\rm max}-k)$$

$k_{\rm max} = 10^8\ \mathrm{Mpc}^{-1}$





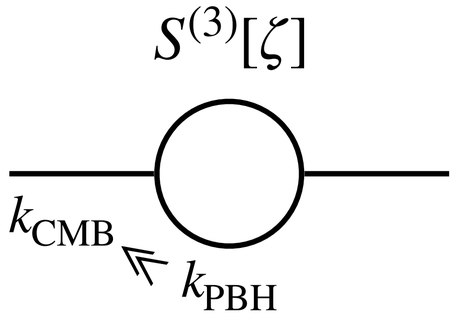
can't reach $\beta = 3$
Atal & Domènech '21

One-loop on CMB

2211.03395

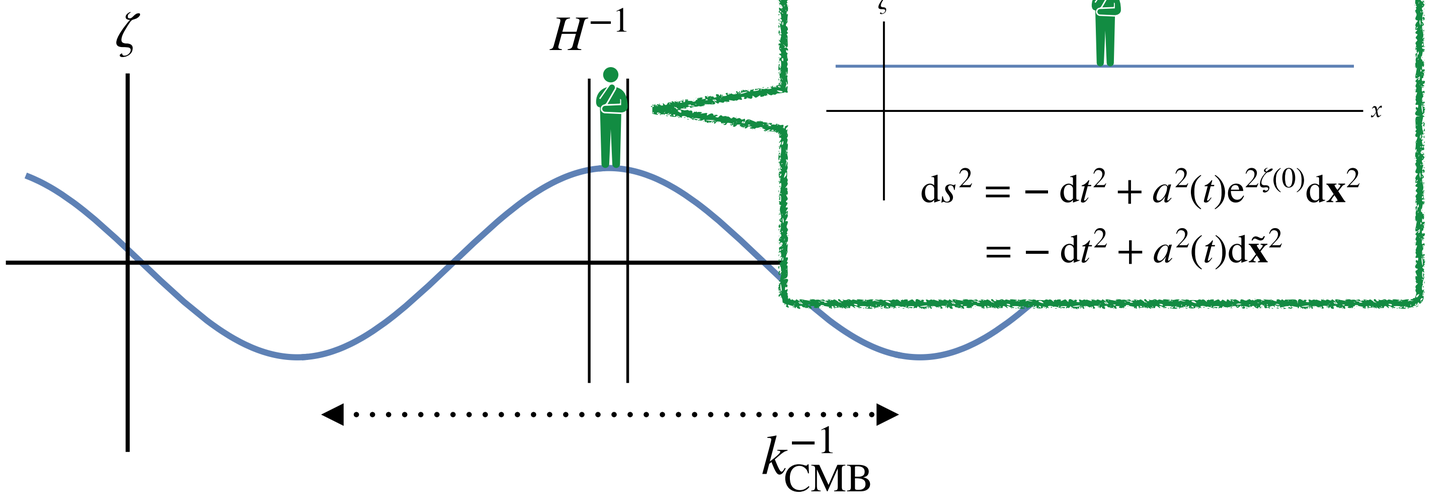
Ruling Out Primordial Black Hole Formation From Single-Field Inflation

Jason Kristiano[1, 2, *] and Jun'ichi Yokoyama[1, 2, 3, 4, †]



$$\mathcal{P}_\zeta^{\rm tree}(k_{\rm CMB}) \sim \Delta\mathcal{P}_\zeta^{1-{\rm loop}}(k_{\rm CMB})$$

Separate U. assumption



- ζ as NG boson of asymptotic dilatation
  (e.g. Assassi, Baumann, Green '12)
- (classically) soft ζ is conserved
  (Lyth, Malik, Sasaki '05)
- Maldacena's consistency relation ('03)

$$S^{(3)}[\zeta] \Rightarrow \langle\zeta_{k_{\rm L}}\zeta_{k_{\rm S}}\zeta_{k_{\rm S}}\rangle \propto \mathcal{P}_\zeta(k_{\rm L})\frac{d\mathcal{P}_\zeta(k_{\rm S})}{d\ln k_{\rm S}}$$

merely scale-redefinition

Loop Cancellation

tensor ver. (Ota, Sasaki, Wang '22 x 2, '23) didn't vanish.....

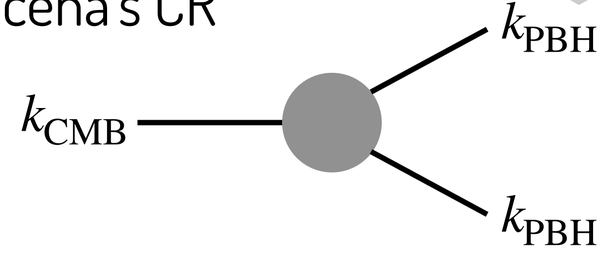
YT, Terada, Tokuda '23

KY

$$S^{(3)}[\zeta] = \int \mathrm{d}^4x \left[\mathcal{O}_{\rm bulk} + \frac{\mathrm{d}}{\mathrm{d}t} \mathcal{O}_{\rm surface} \right]$$

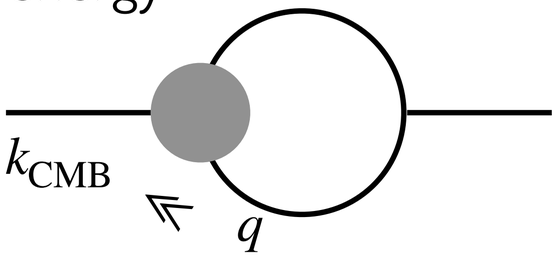
cf. Arroja & Tanaka '11

Maldacena's CR



$$\propto \mathcal{P}_\zeta(k_{\rm CMB}) \frac{\mathrm{d}\mathcal{P}_\zeta(k_{\rm PBH})}{\mathrm{d}\ln k_{\rm PBH}}$$

Self-energy



$$\propto \mathcal{P}_\zeta(k_{\rm CMB}) \int \mathrm{d}\ln q \frac{\mathrm{d}\mathcal{P}_\zeta(q)}{\mathrm{d}\ln \mathrm{q}} = \mathcal{P}_\zeta(k_{\rm CMB}) \left(\mathcal{P}_\zeta(k \to \infty) - \mathcal{P}_\zeta(k \overset{<}{\sim} k_{\rm CMB}) \right)$$

$i\varepsilon$ prescription 10^{-9}

Ward—Takahashi of Asymptotic Dilatation

tree ζ conservation ⇔ Maldacena's CR ⇔ self-energy cancellation

Summary

1. Sub-Solar PBHs may be detected
2. Asteroid PBH-DM can be checked by induced GW
   w/ LISA & DECIGO
   Many theoretical progresses