2023.09.01 @ PPP

原始ブラックホール研究の最前線

— 原始ブラックホールは自然科学なのか？ —

名古屋大学 高等研究院・物理 C 研

多田 祐一郎

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

"Listening to the dark Universe: black holes in the era of gravitational-wave astronomy"

注意事項

原始ブラックホールは･･･

・・・

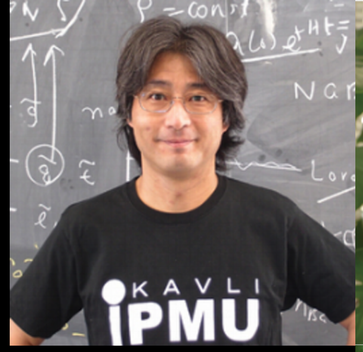
- 仮説上のブラックホール
- 作り得る物理も検証されていない
- 死なない

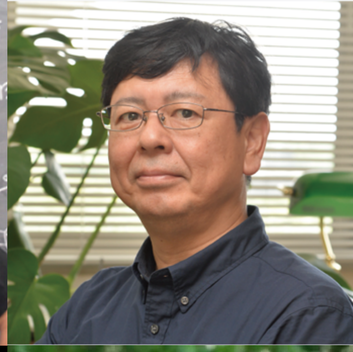
でもあれば楽しい･･･!

内容

1. 自己紹介
2. 暗黒物質としての原始ブラックホール
3. インフレーションと原始ブラックホール
4. 最近の話
5. まとめ

多田 祐一郎 (ただ ゆういちろう)






’08-’12	東京大学理学部物理学科	
’12-’17	東京大学院	村山斉 (IPMU), 川崎雅裕 (ICRR)
’17-’18	パリ天体物理学研究所	S. Renaux-Petel
’18-’21	名古屋大学 (学振 PD)	杉山直
’21-	名古屋大学 (YLC 特任助教)	市來淨與

- 初期宇宙の理論研究

  = インフレーション　↔ 観測

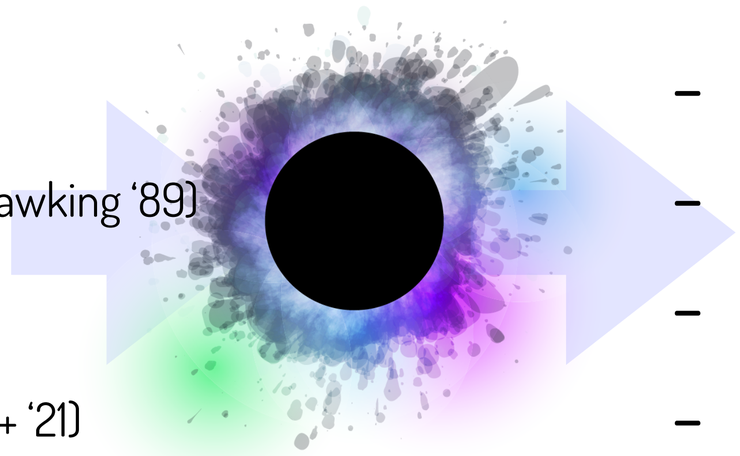
2. 暗黒物質としての原始ブラックホール

原始ブラックホール

Carr & Hawking '74

- ～ $\mathcal{O}(1)$ 密度ゆらぎ (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)

⋮



星形成前

原始ブラックホール

(Primordial Black Hole)

- 暗黒物質 (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)

⋮

原始ブラックホール

Carr & Hawking '74

- ～ $\mathcal{O}(1)$ 密度ゆらぎ (Carr '7
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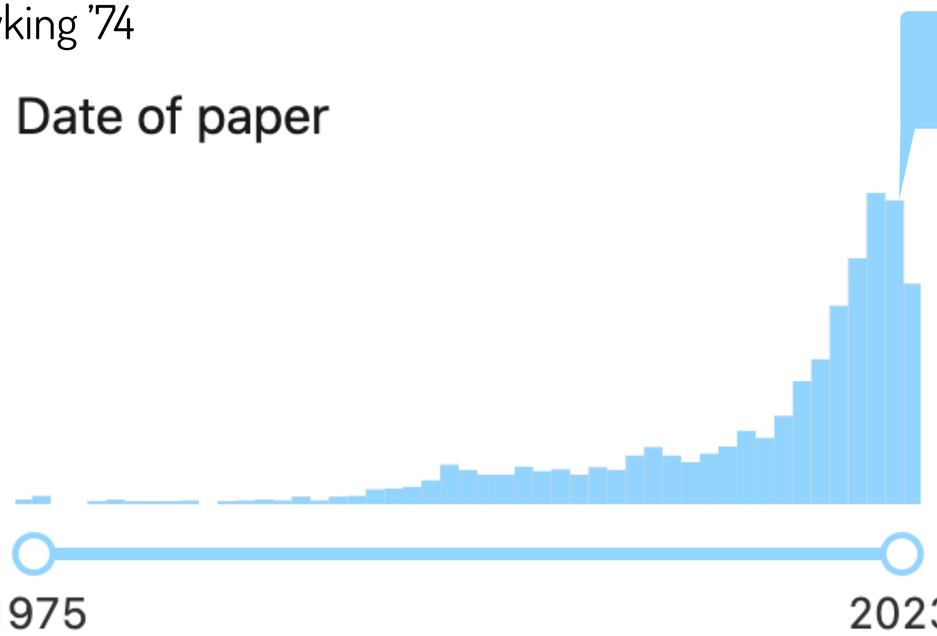
⋮



- 暗黒物質 (Chapline '75)
- K merger GW? (Sasaki+ '16)
- 1BH seeds? (Düchting '04)
- LE lensing obj.? (Niikura+ '19)
- anet 9? (Scholtz & Unwin '19)
- Trigger of r-process? (Fuller+ '17)
- Baryogenesis? (Baumann+ '07)
- JWST luminous gals? (Hutsi+ '22)

⋮

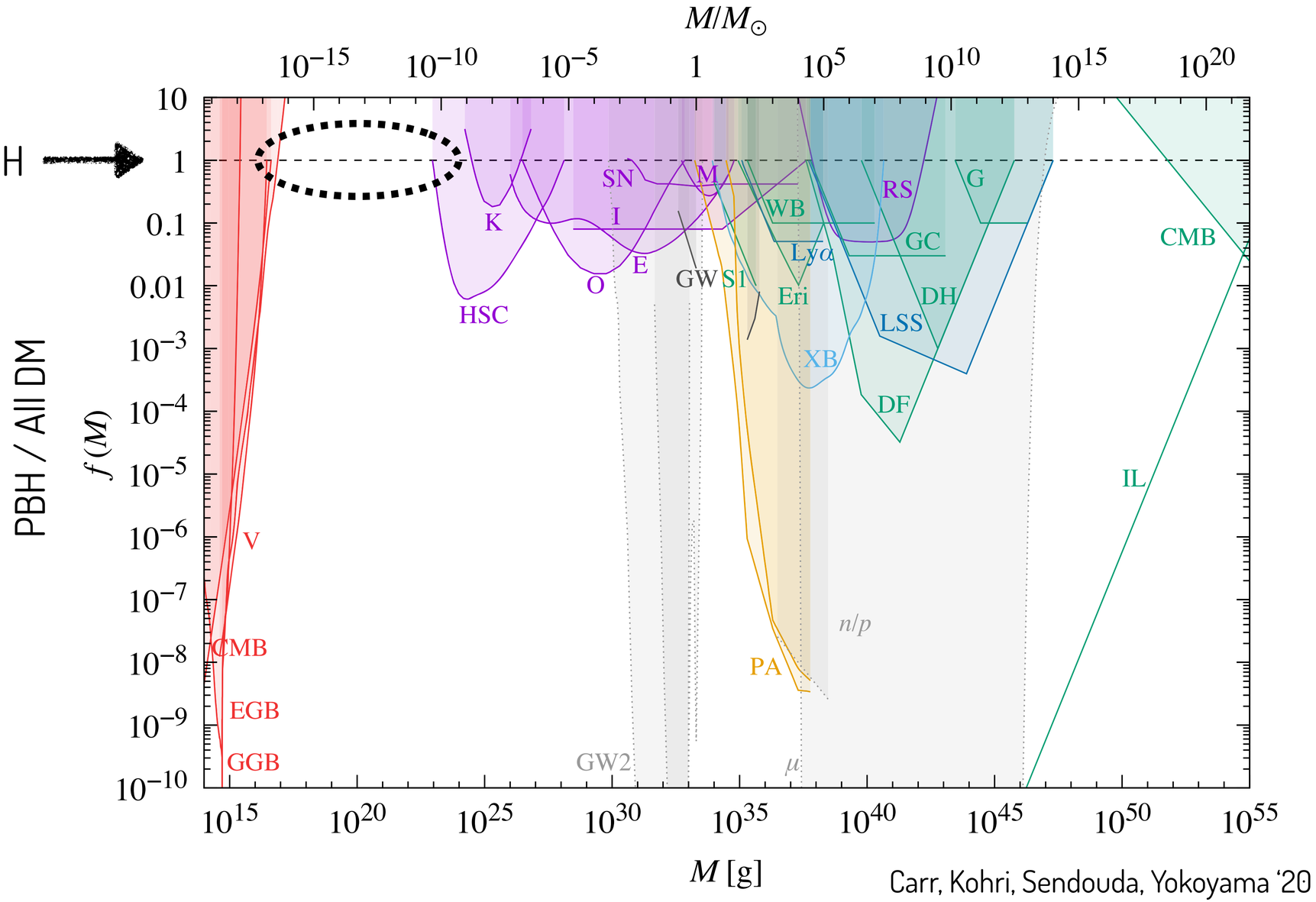
星形成前

原始ブラックホール

(Primordial Black Hole)

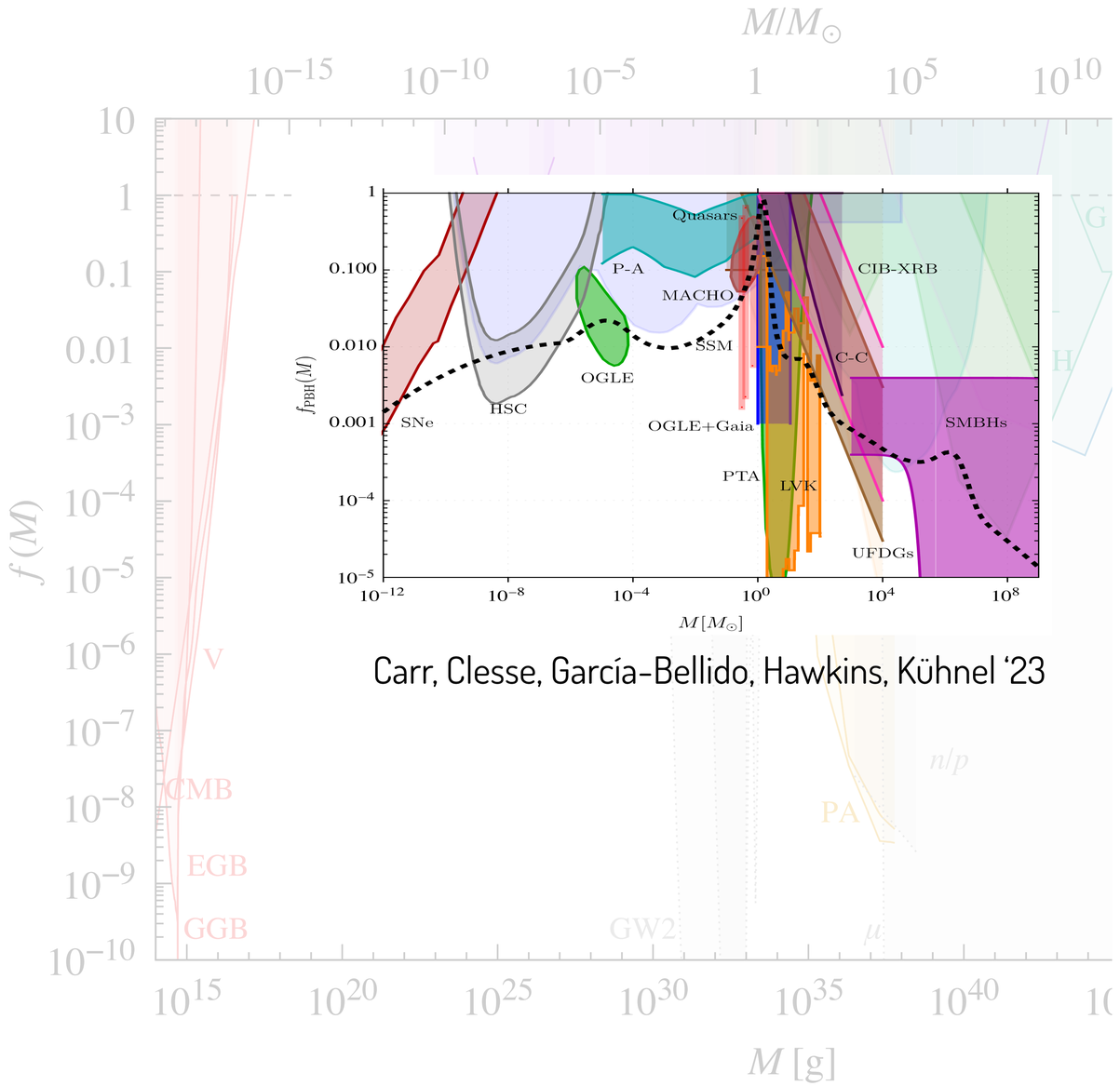
観測制限

All DM = PBH

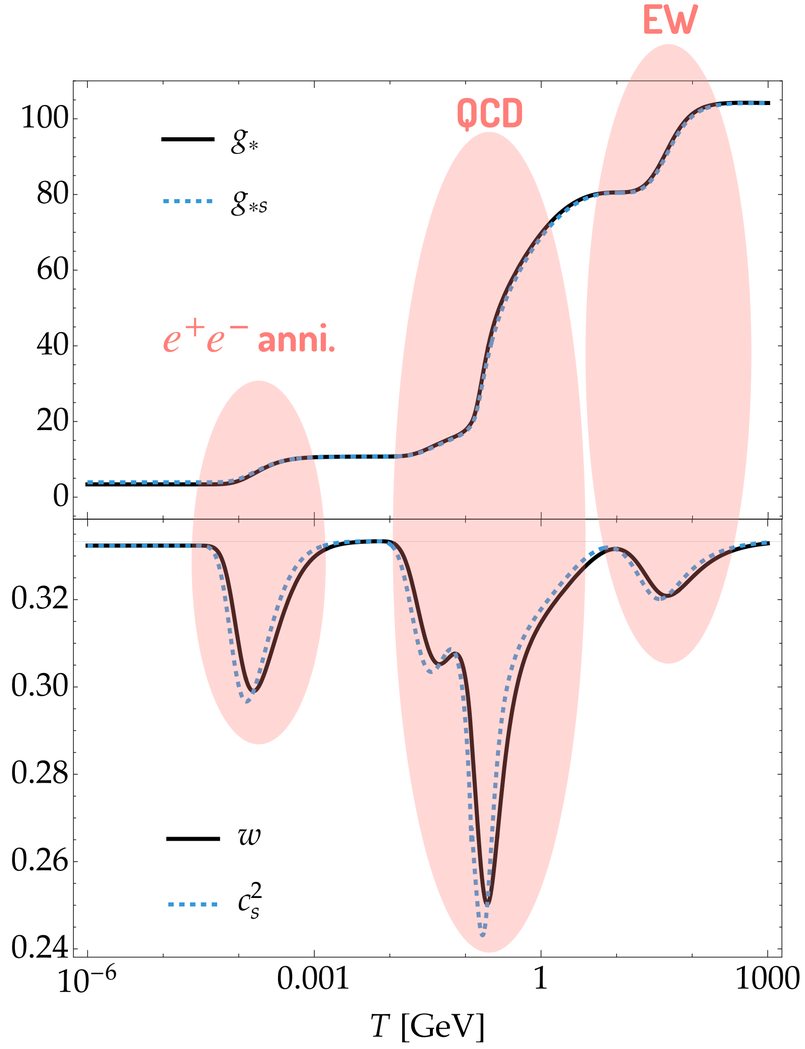


Carr, Kohri, Sendouda, Yokoyama '20

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

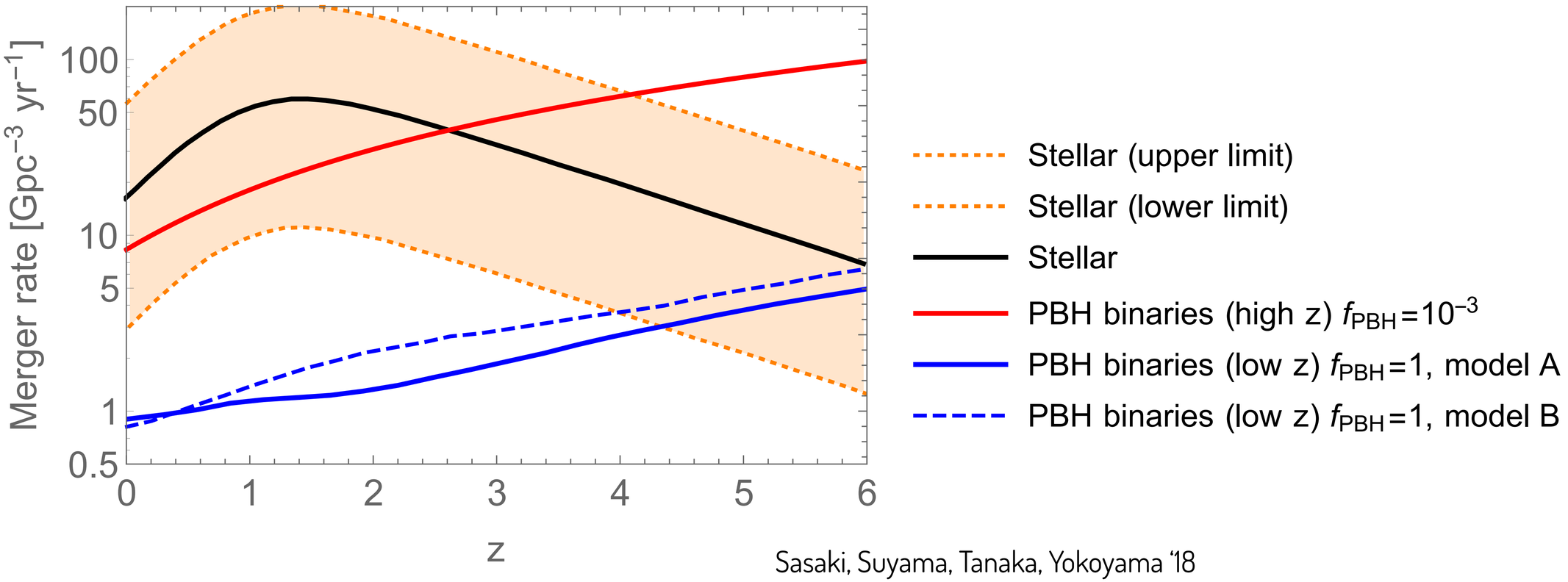
Phukon+ '21

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

高赤方偏移



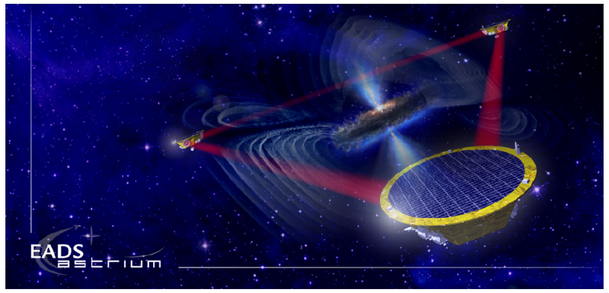
Sasaki, Suyama, Tanaka, Yokoyama '18

(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.



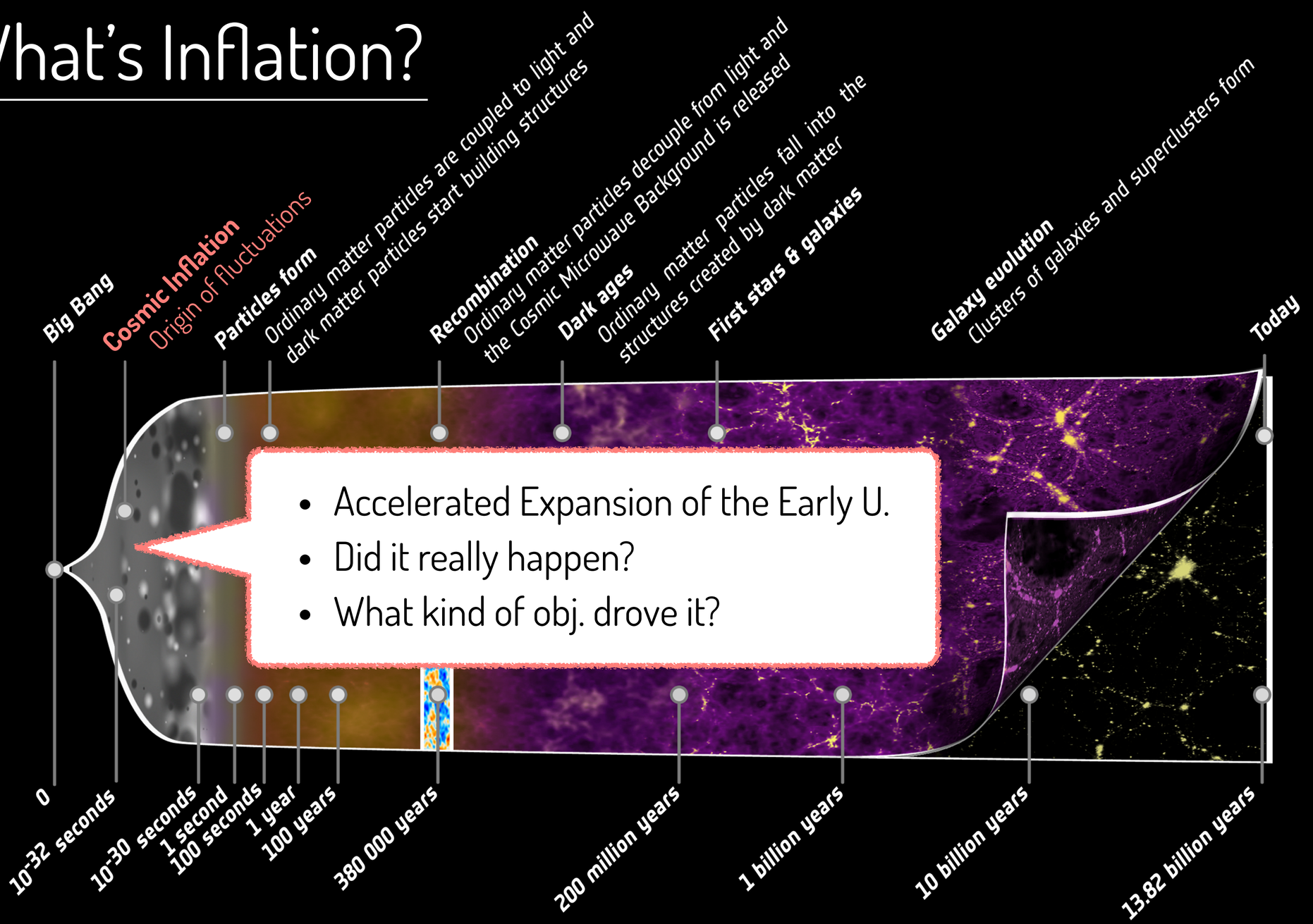
LISA

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

Radiation Era

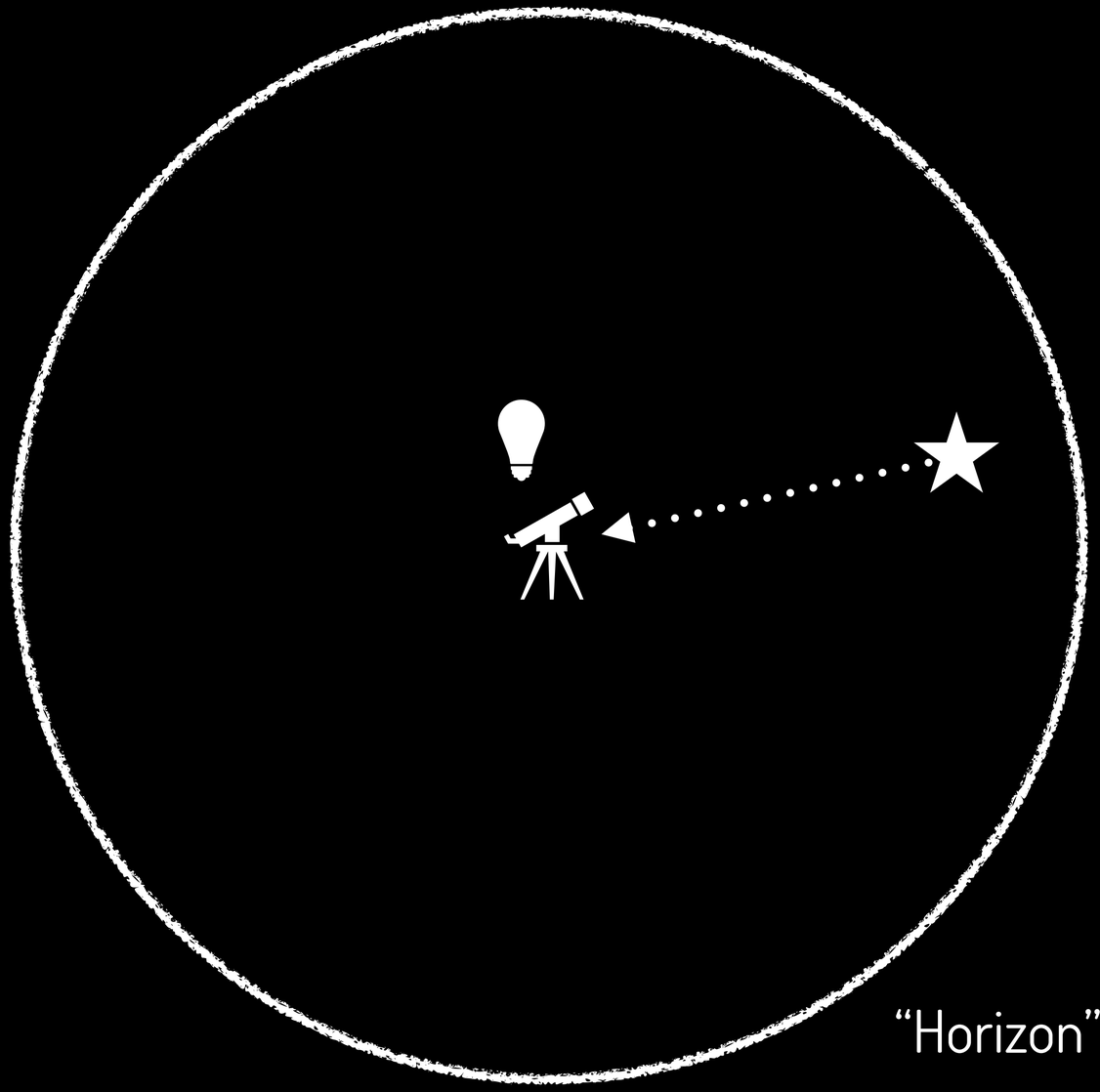
3. インフレーションと原始ブラックホール

What's Inflation?



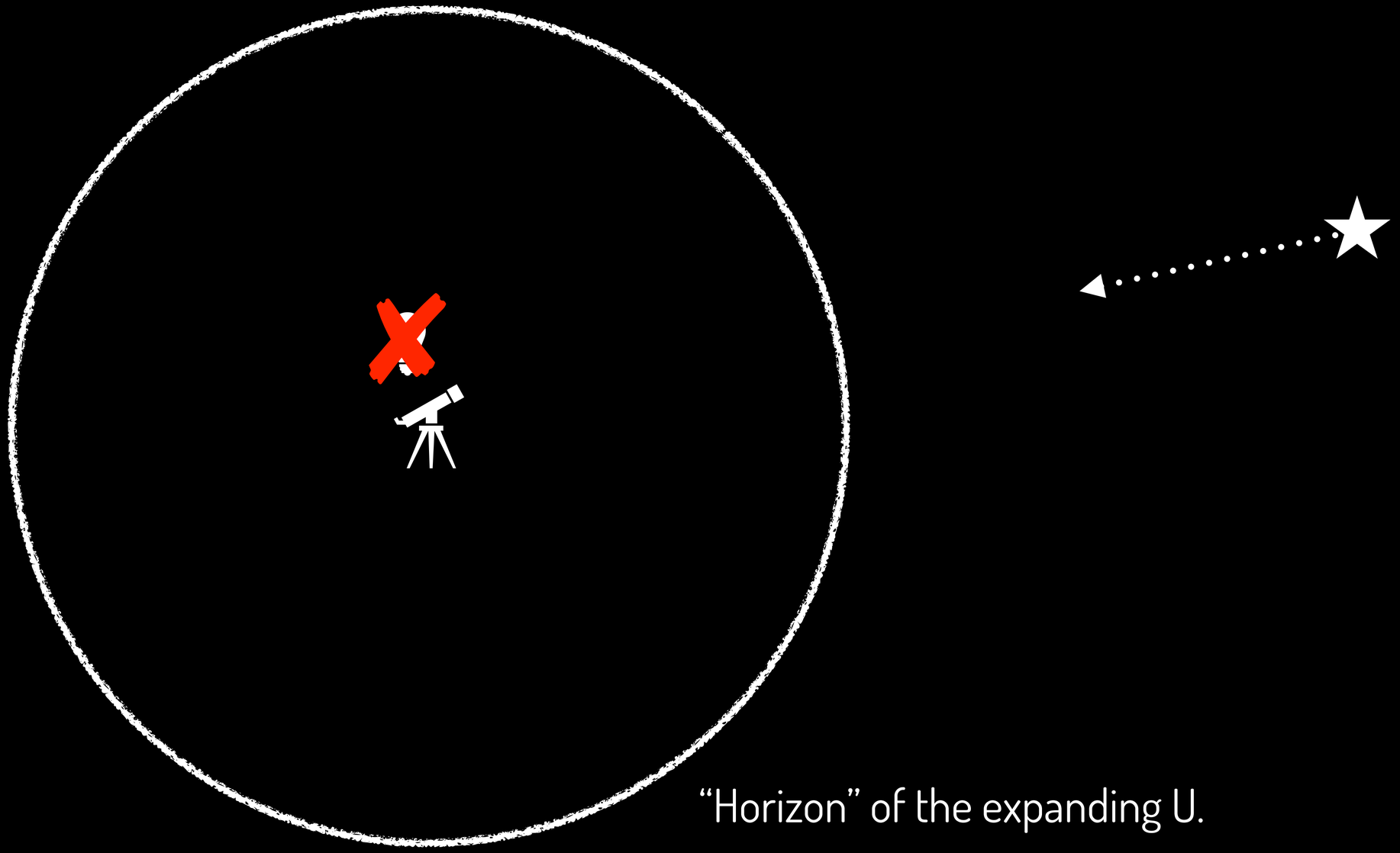
- Accelerated Expansion of the Early U.
- Did it really happen?
- What kind of obj. drove it?

Generation of PTB



“Horizon” of the expanding U.

Generation of PTB



“Horizon” of the expanding U.

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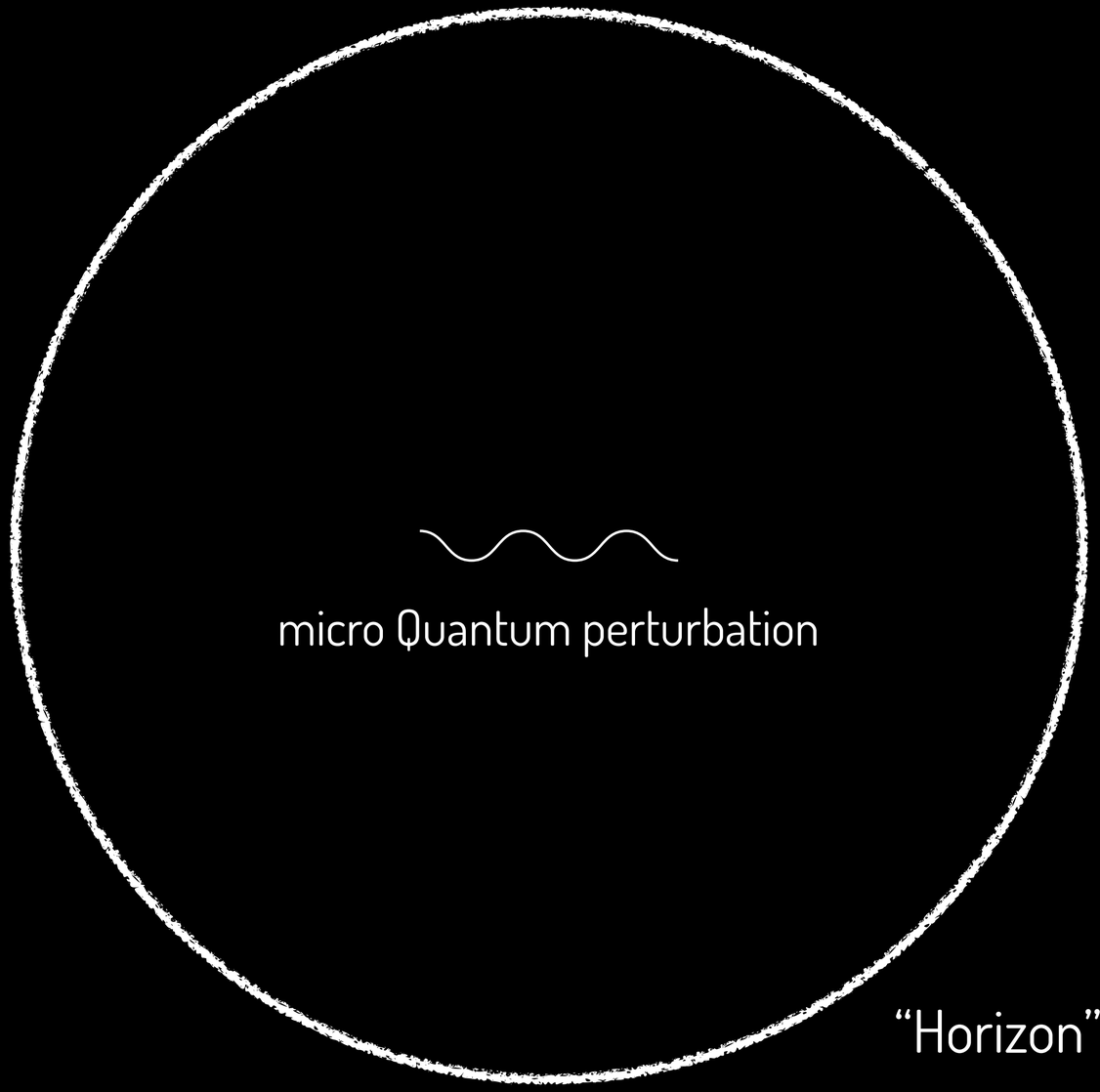

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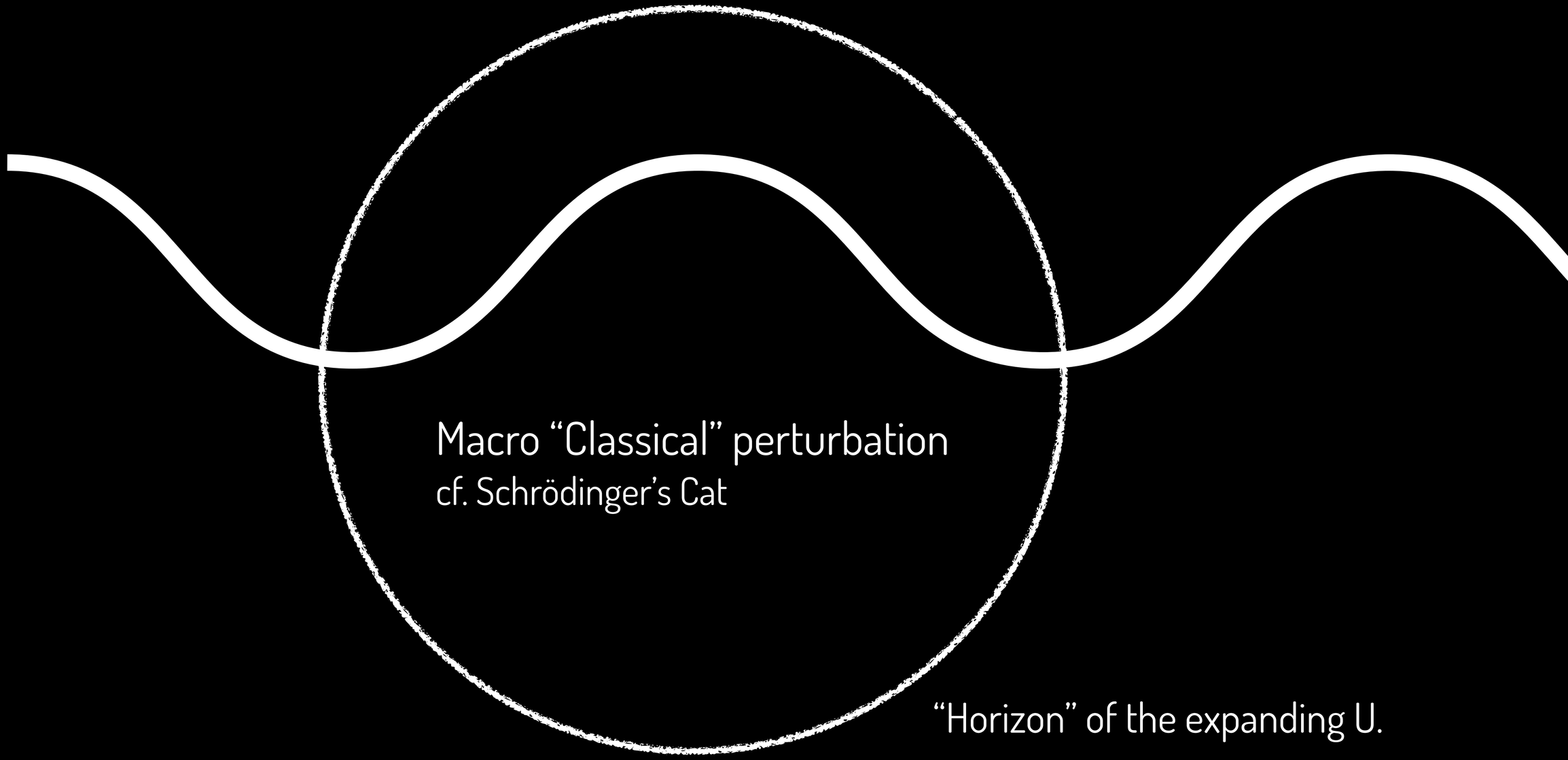
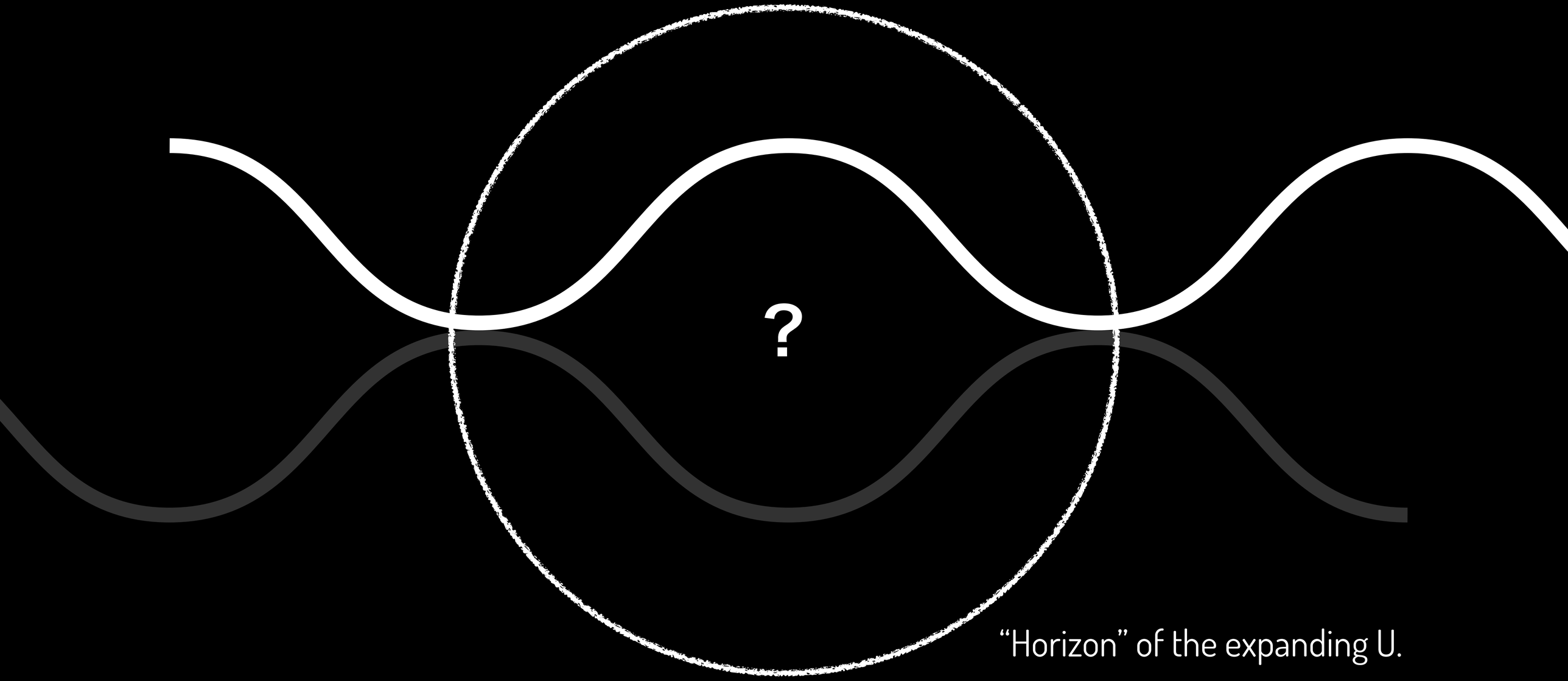


Generation of PTB



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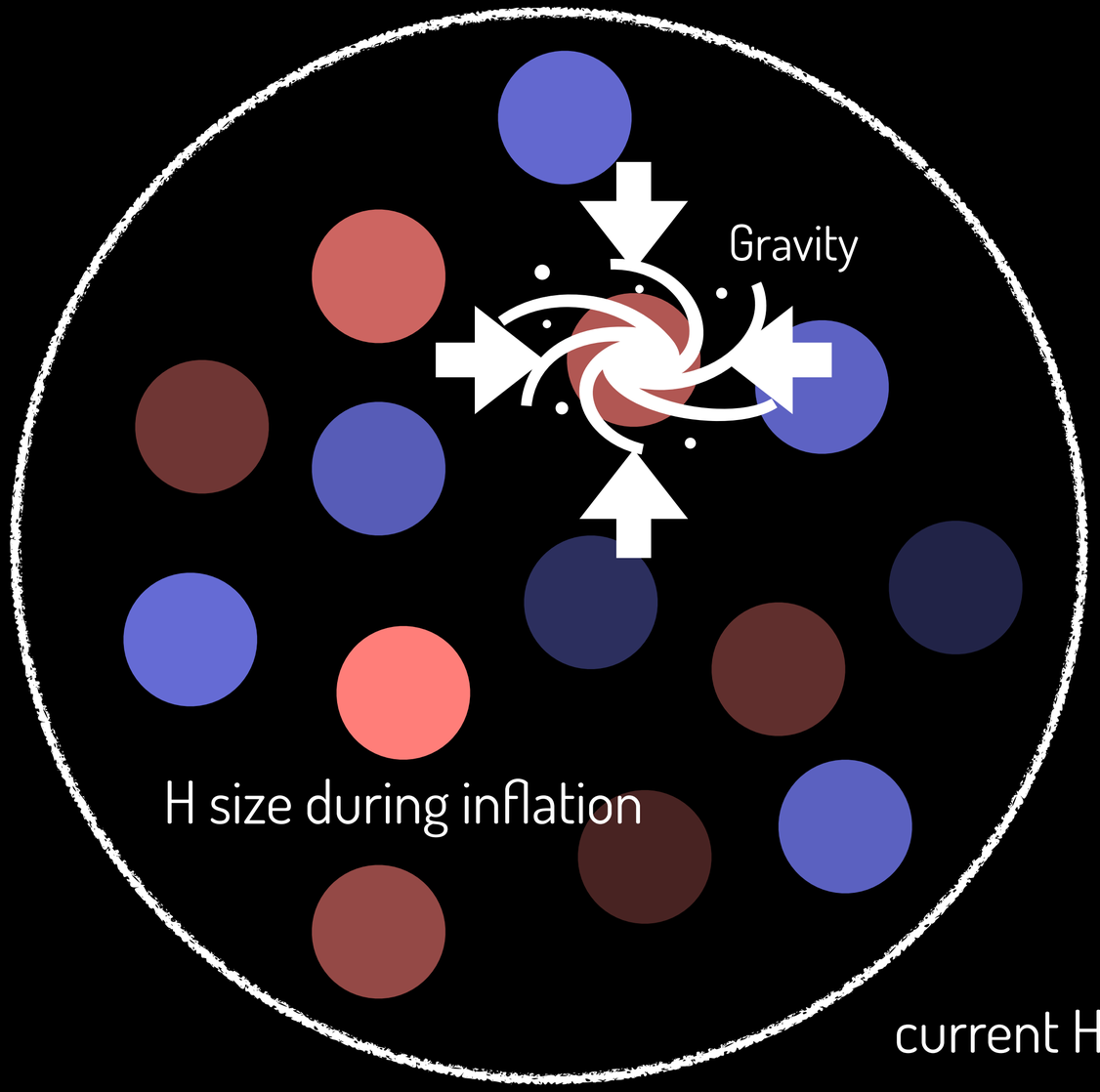
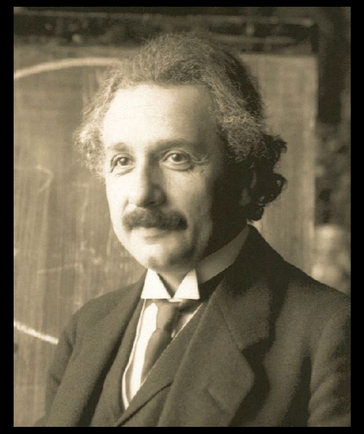
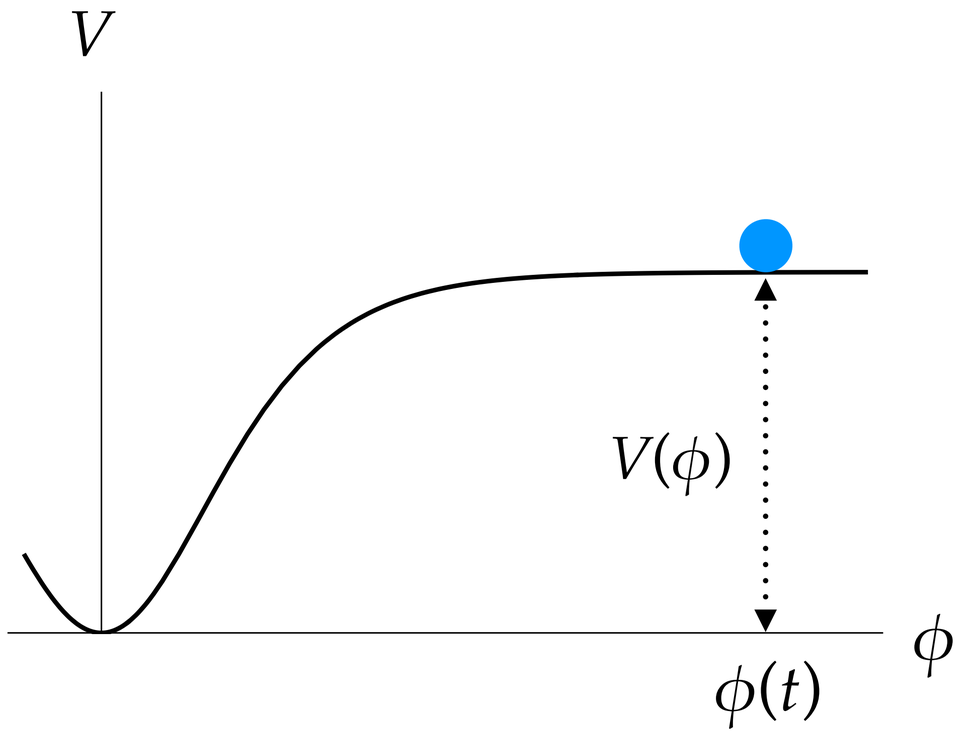




Energy = Mass

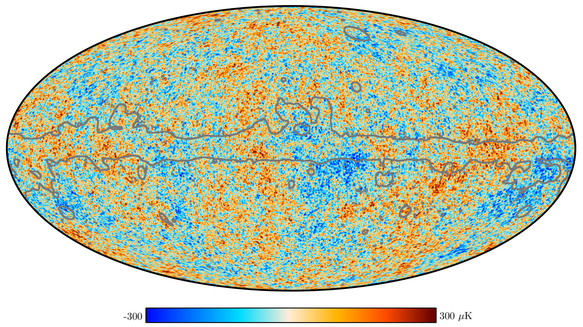
Inflation Theories

Just to realise an Accelerated Expansion (= Dark Energy = almost const. energy), you only need homogeneous VEV of some scalar $\phi(t)$ with the potential $V(\phi)$.



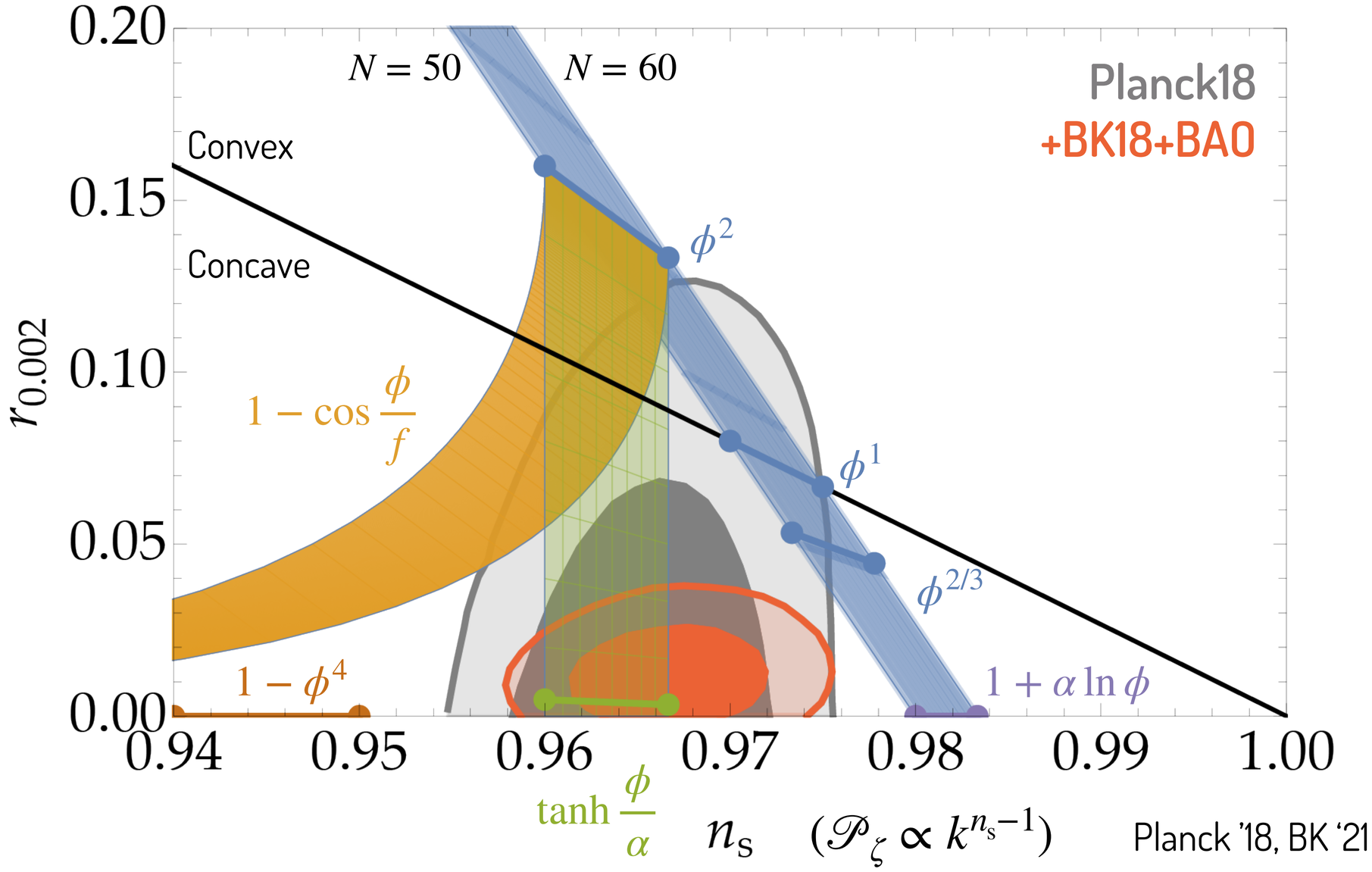
"Inflation of the # of inflation theories"
by T. Matsubara

Latest CMB const.

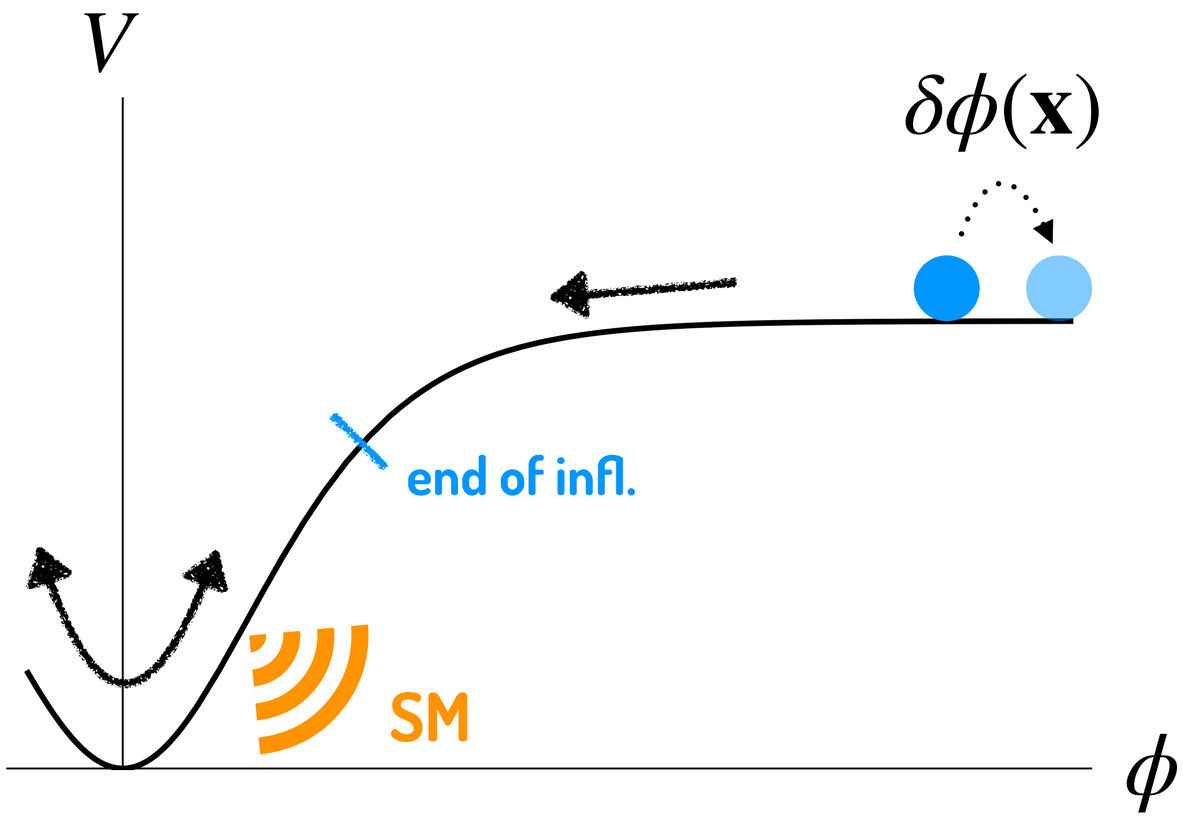


$$T = 2.725\,\mathrm{K} \pm 18\,\mu\mathrm{K}$$

$$\Rightarrow \mathscr{P}_\zeta = 2.1 \times 10^{-9}$$



Large PTB?



Lyth, Malik, Sasaki '05

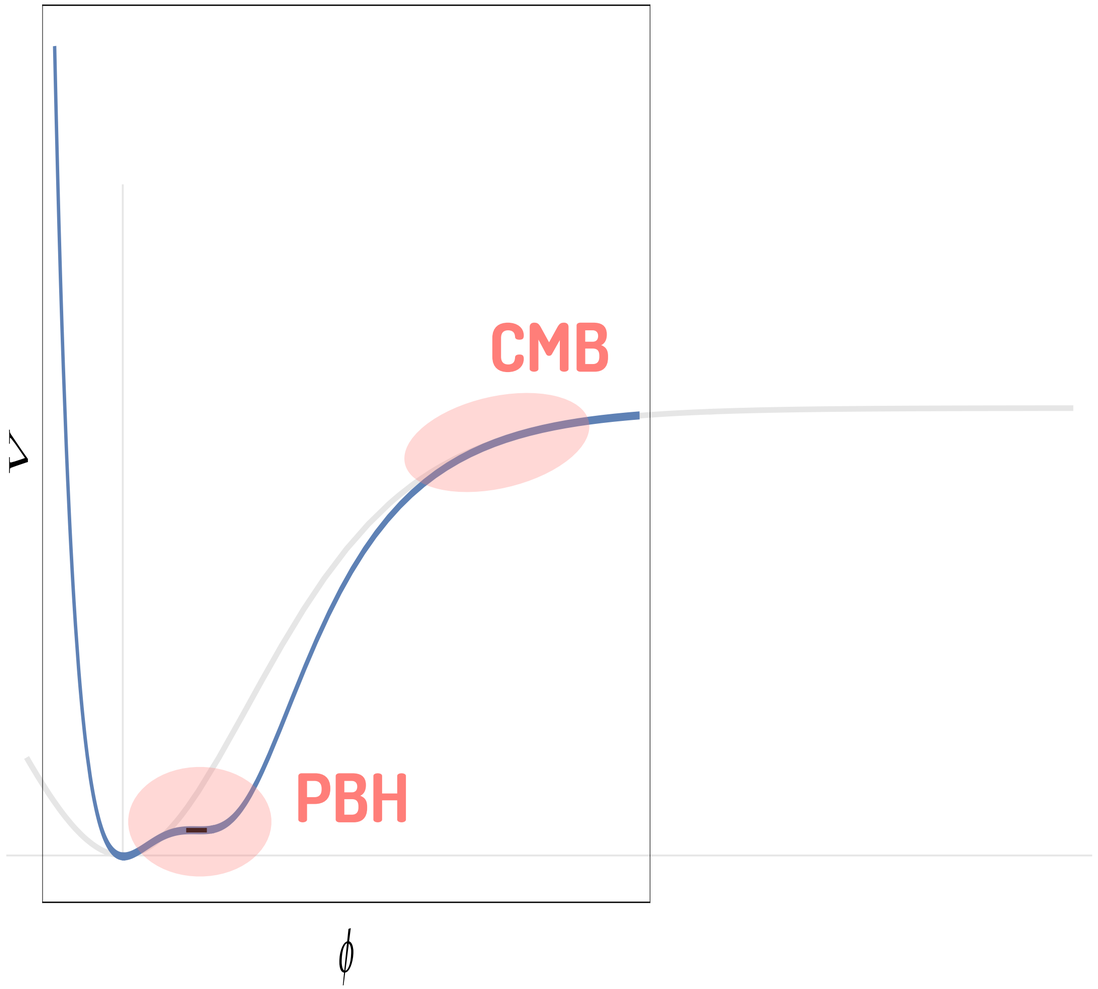
- 時間のずれ $\delta N(\mathbf{x})$ は超ホライズン保存量
- 曲率ゆらぎ $\zeta(\mathbf{x})$ に等しい

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

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

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

Large PTB?



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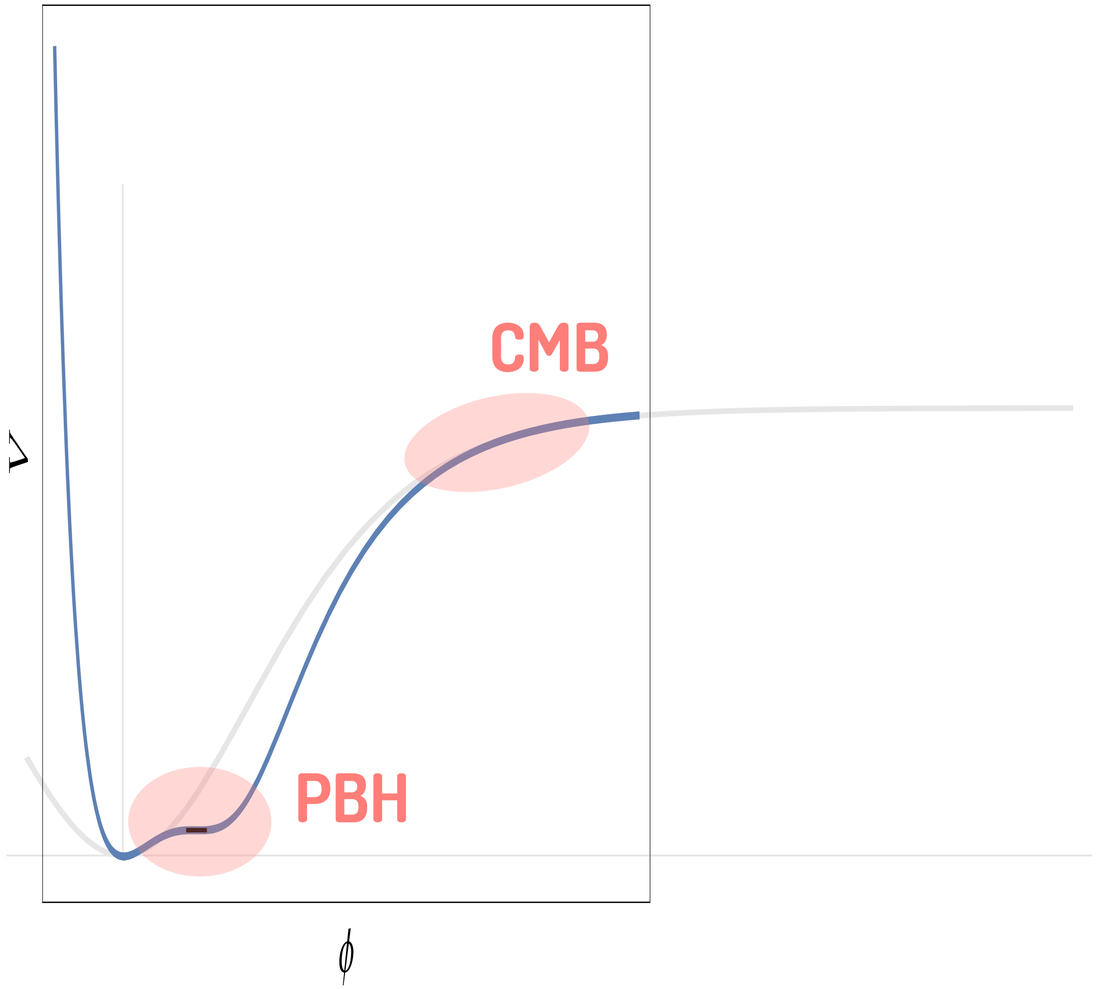
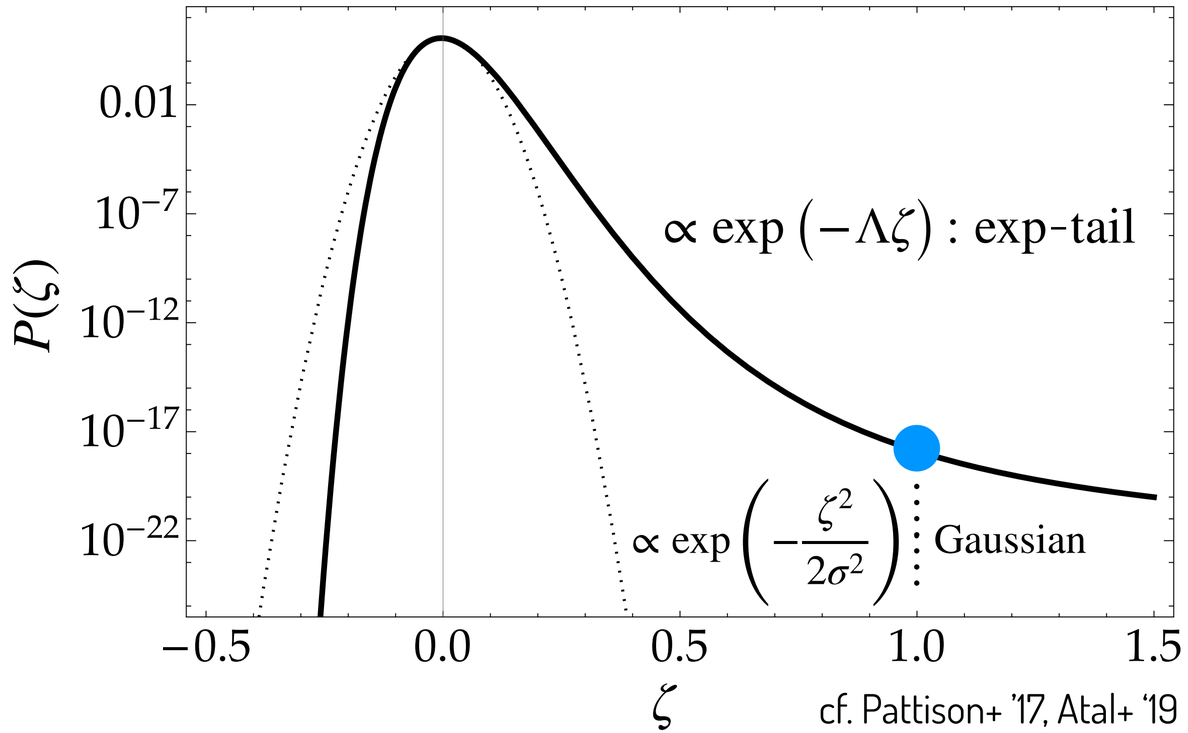
Exp.-tail

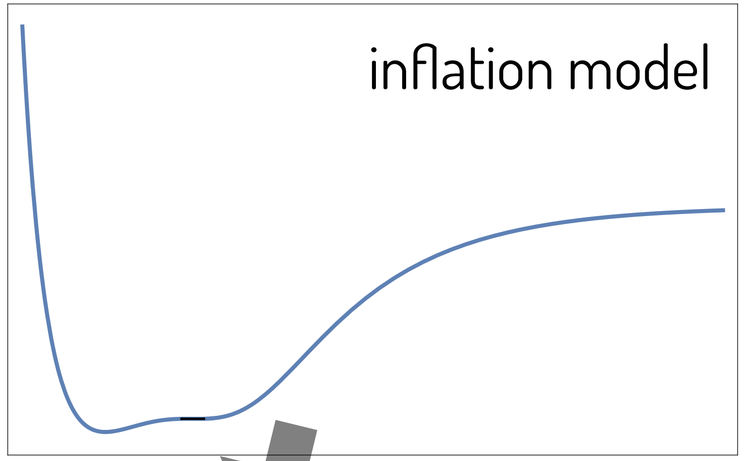


$\dot{\phi}$ is reducing → $\delta\phi$'s effect is asymmetric!



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

Triangle study

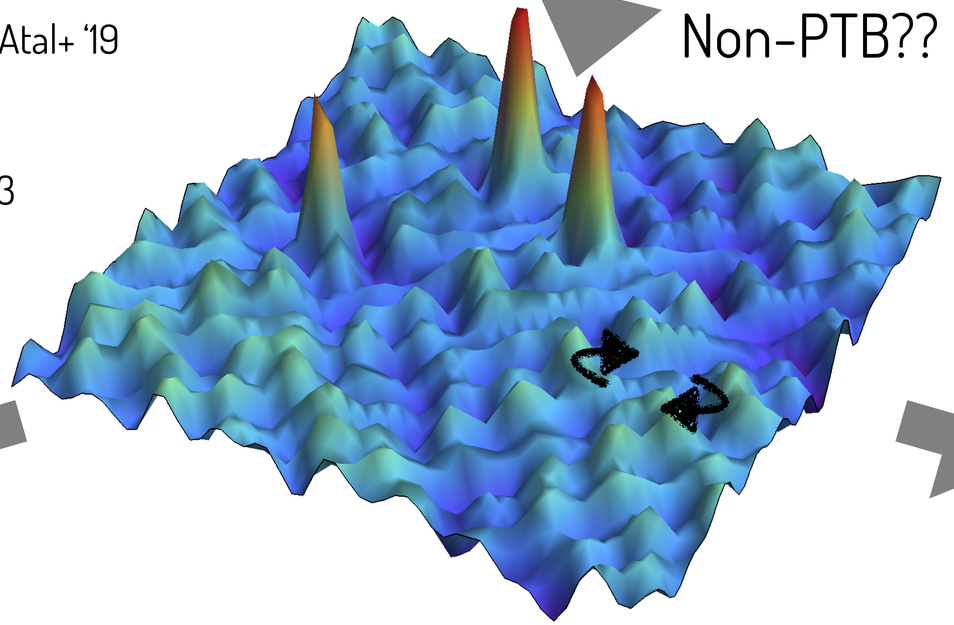


Non-PTB??

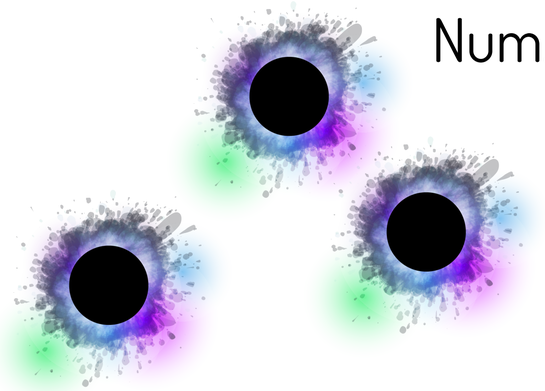
$$\mathscr{C}(r) = \frac{2}{3}\left[1 - (1 + r\zeta'(r))^2\right]$$

$$\bar{\mathscr{C}} = \frac{1}{V_{R_\mathrm{m}}}\int_0^{R_\mathrm{m}} 4\pi R^2 \mathscr{C}\,\mathrm{d}R > \bar{\mathscr{C}}_\mathrm{th} = \frac{2}{5}$$ Atal+ '19

$$M \sim M_{R_\mathrm{m}}(\bar{\mathscr{C}} - \bar{\mathscr{C}}_\mathrm{th})^{0.36}$$ Choptuik+ '93



Num. Rel.



PBH abundance

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

Ω_GW

induced GW b.g.

indirect evidence

確率形式

Starobinsky '86

= 超ホライズン粗視化場のEFT

= 局所的に一様等方 + 相関ありブラウン運動

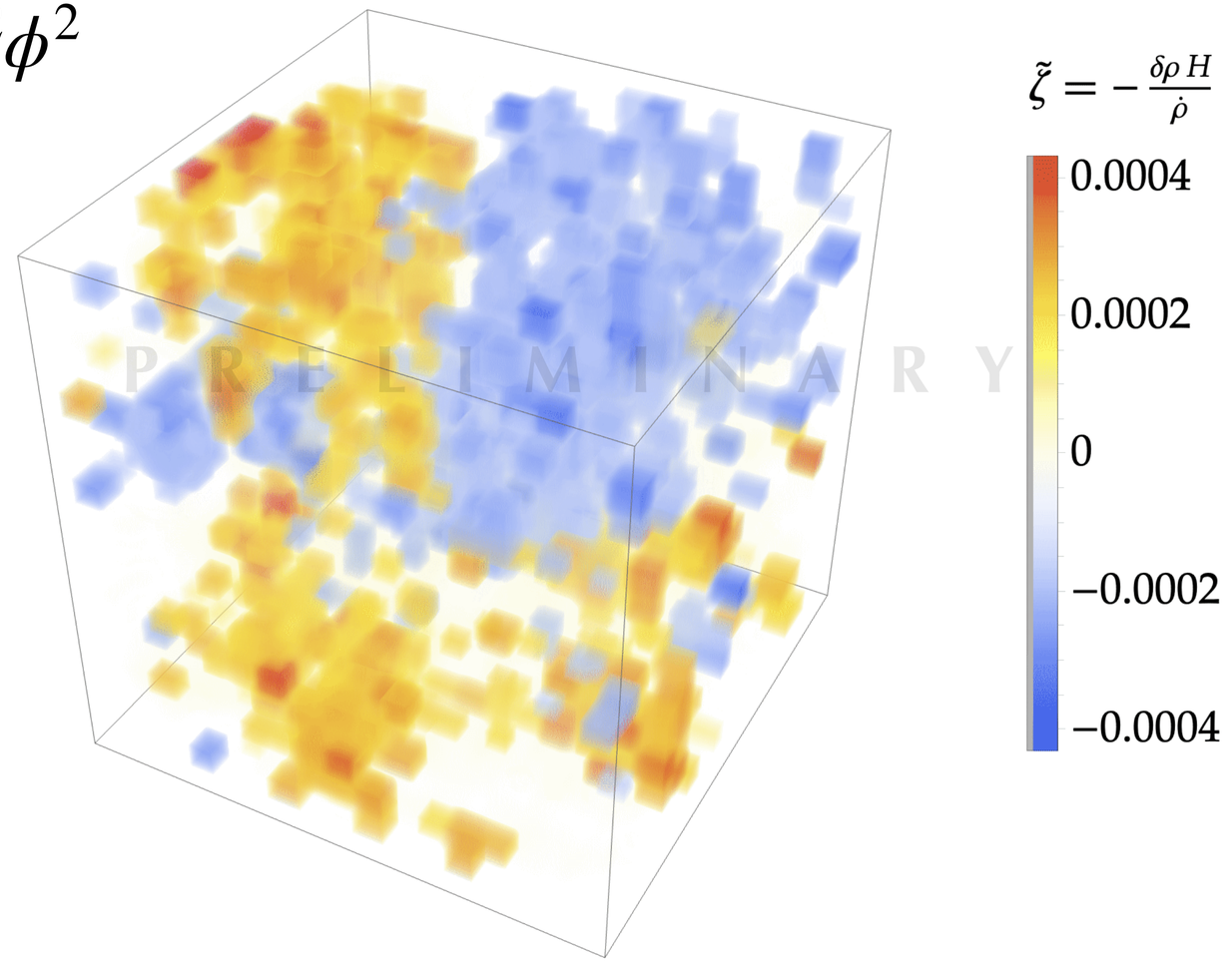
$$
\begin{cases}
\mathrm{d}\phi(N,\mathbf{x}) &= \dfrac{\pi(N,\mathbf{x})}{H(N,\mathbf{x})}\mathrm{d}N + \dfrac{H(N,\mathbf{x})}{2\pi}\mathrm{d}W(N,\mathbf{x}), \\
\mathrm{d}\pi(N,\mathbf{x}) &= \left(-3\pi(N,\mathbf{x}) - \dfrac{V'(\phi(N,\mathbf{x}))}{H(N,\mathbf{x})}\right)\mathrm{d}N, \\
3M_{\mathrm{Pl}}^2H^2(N,\mathbf{x})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

STOLAS

Mizuguchi, Murata, YT in prep.

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

$N = 5.5$



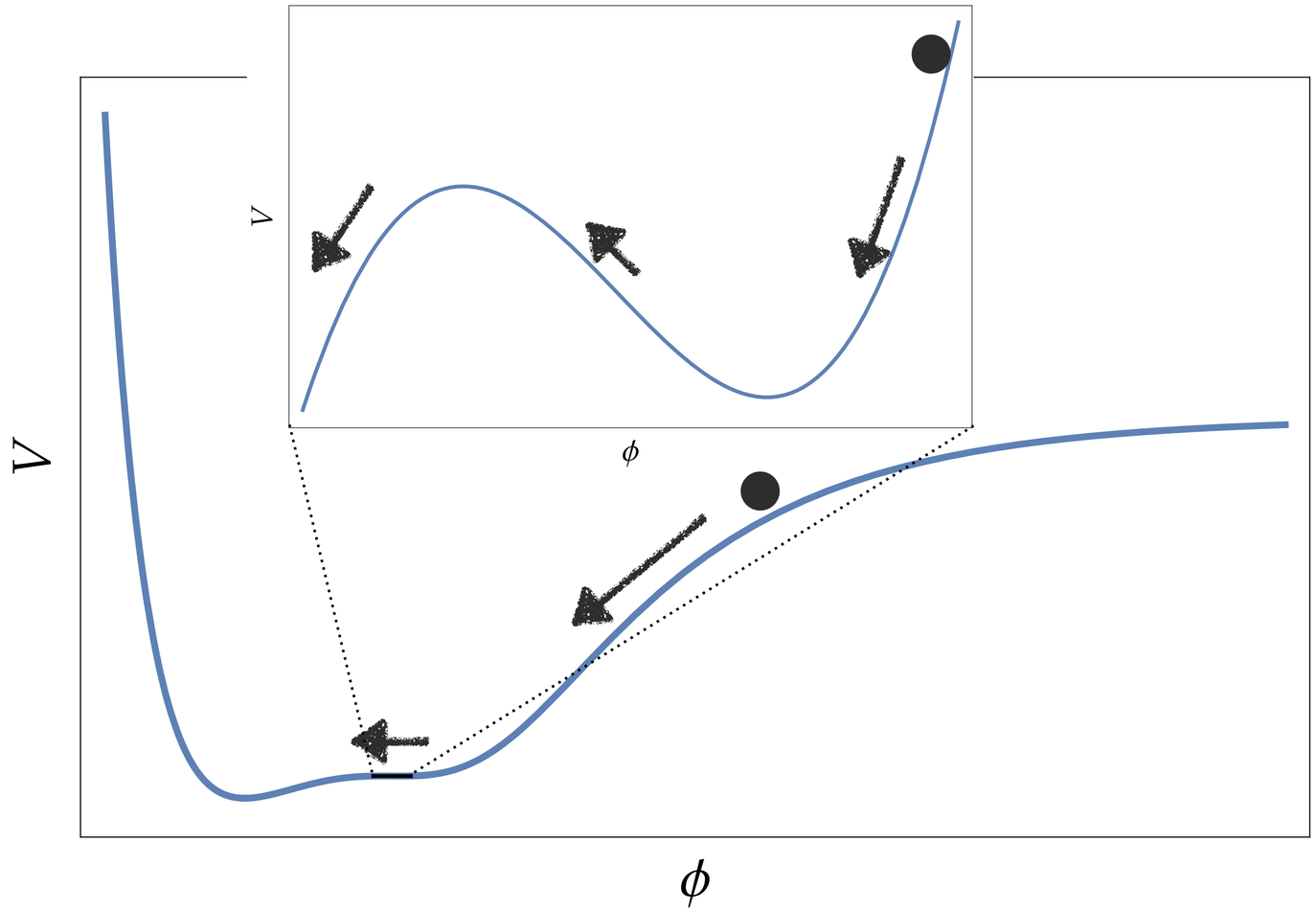
STOLAS

Mizuguchi, Murata, YT in prep.

$$V = \frac{W_0^2}{\mathscr{V}3}\left[\frac{c_{\rm up}}{\sqrt[3]{\mathscr{V}}} + \frac{a_{\rm w}}{e^{\frac{\phi}{\sqrt{3}}} - b_{\rm w}} - \frac{c_{\rm w}}{e^{\frac{\phi}{\sqrt{3}}}} + \frac{e^{\frac{2\phi}{\sqrt{3}}}}{\mathscr{V}}\left(d_{\rm w} - \frac{g_{\rm w}}{r_{\rm w}e^{\sqrt{3}\phi}/\mathscr{V} + 1}\right)\right]$$

Cicoli+ '18, Biagetti+ '18

Ex. 2: Inflection

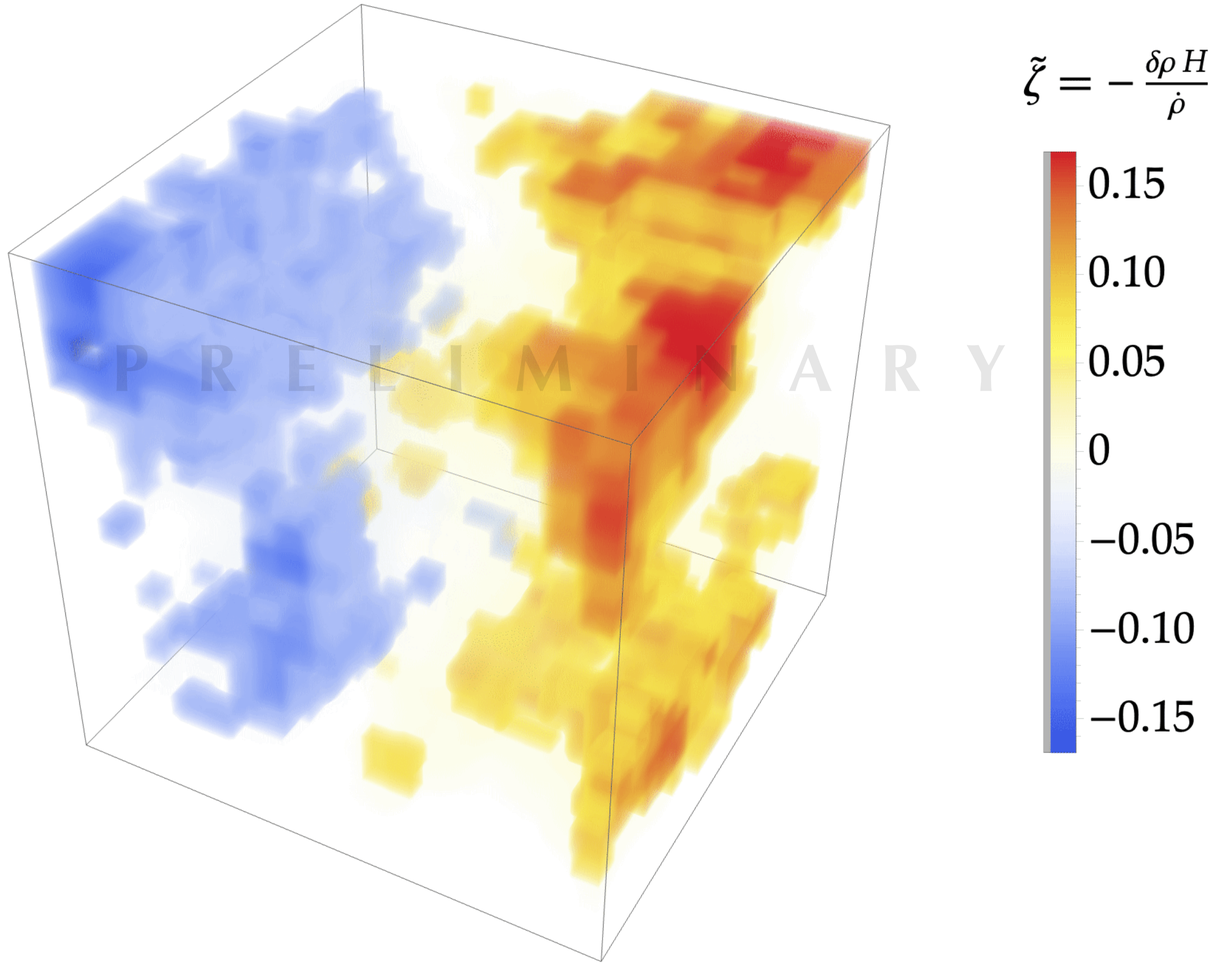


STOLAS

Mizuguchi, Murata, YT in prep.

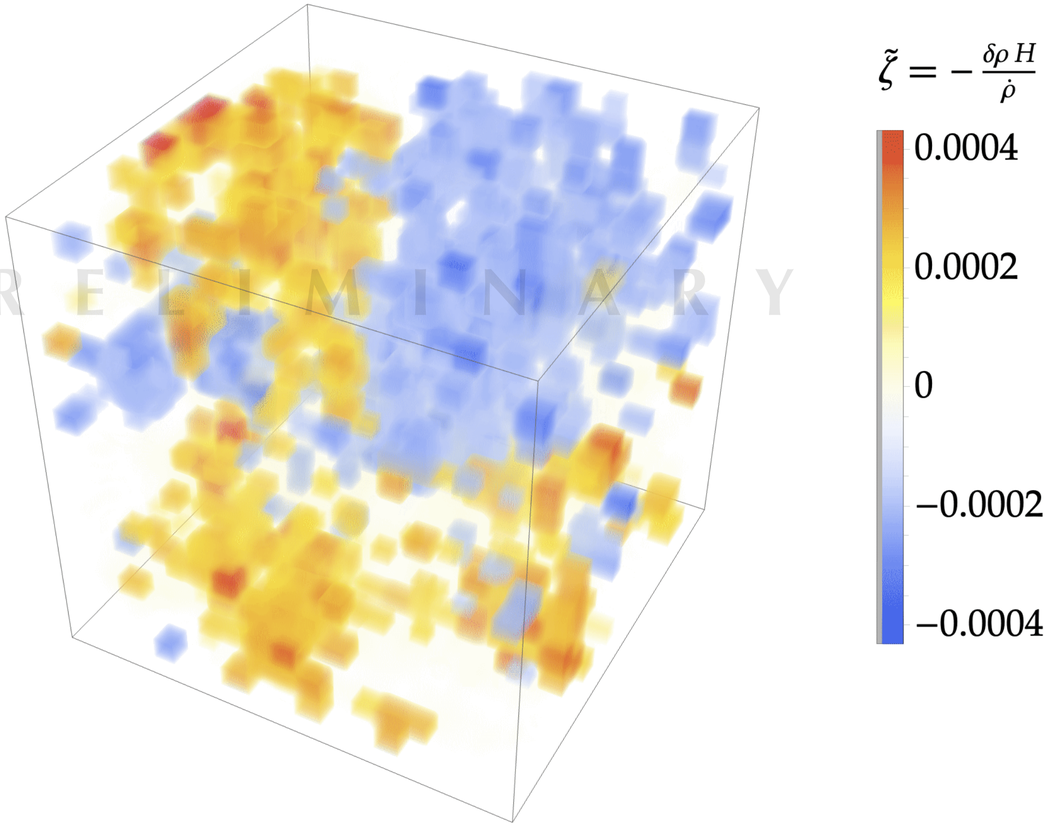
Ex. 2: Inflection

$N = 5.5$



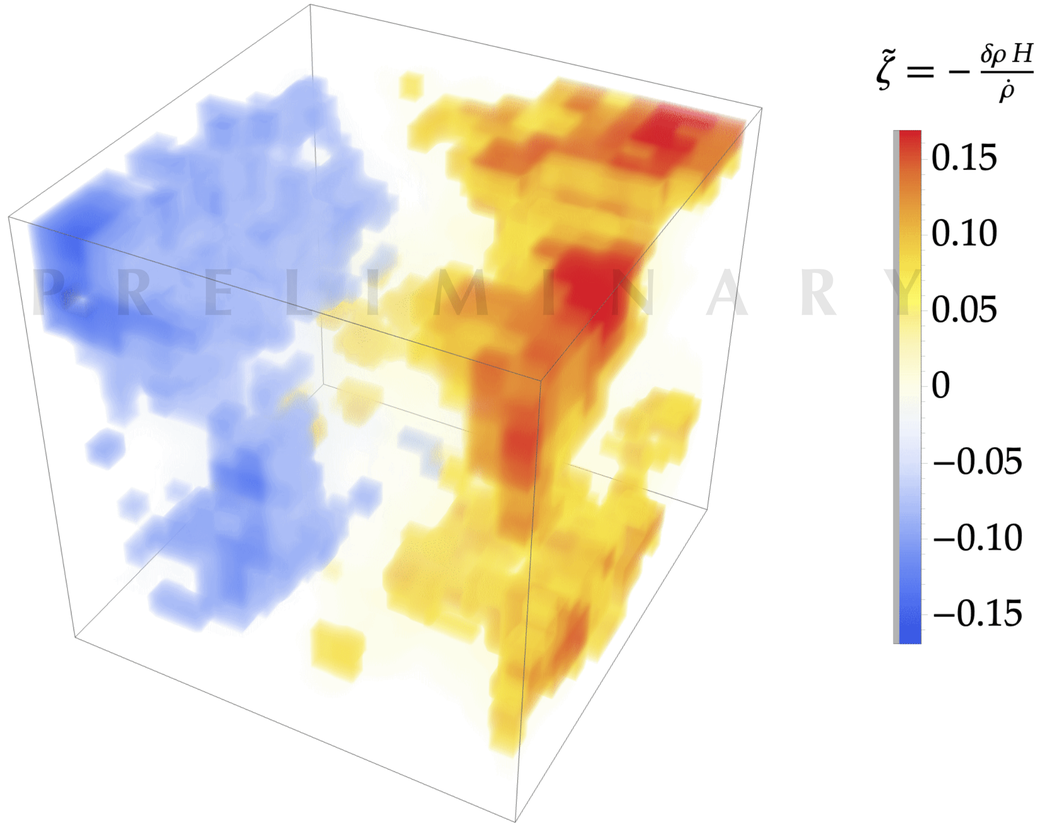
Ex. 1 : Chaotic

$N = 5.5$



Ex. 2 : Inflection

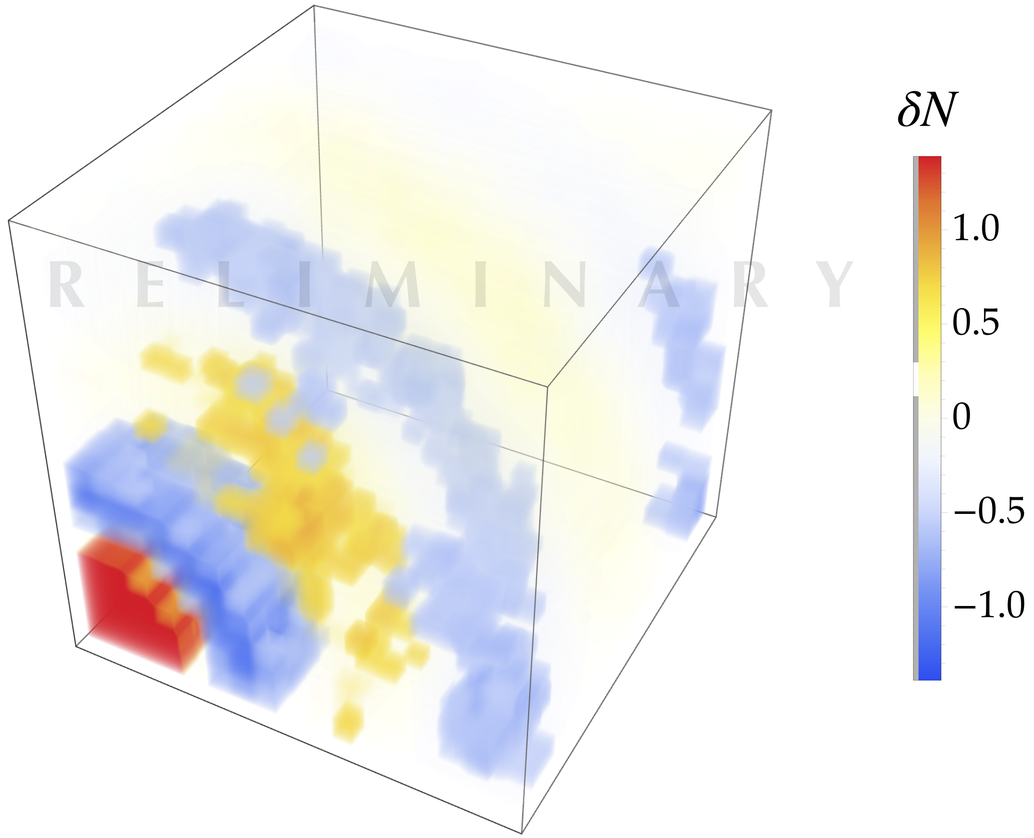
$N = 5.5$



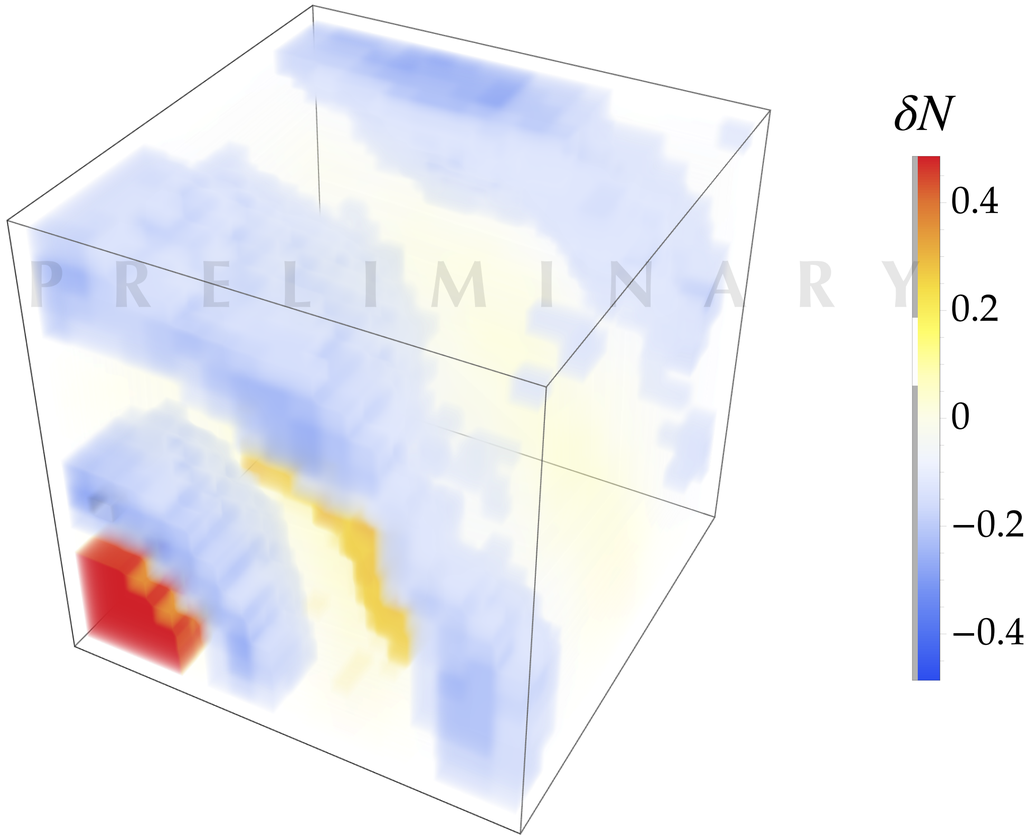
Importance Sampling

Intentionally large noise @ $N = 3$

Ex. 1 : Chaotic



Ex. 2 : Inflection



Importance Sampling

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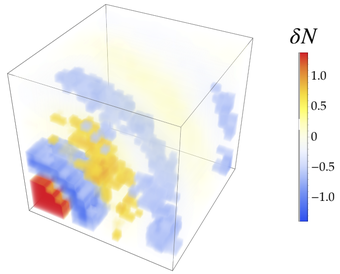
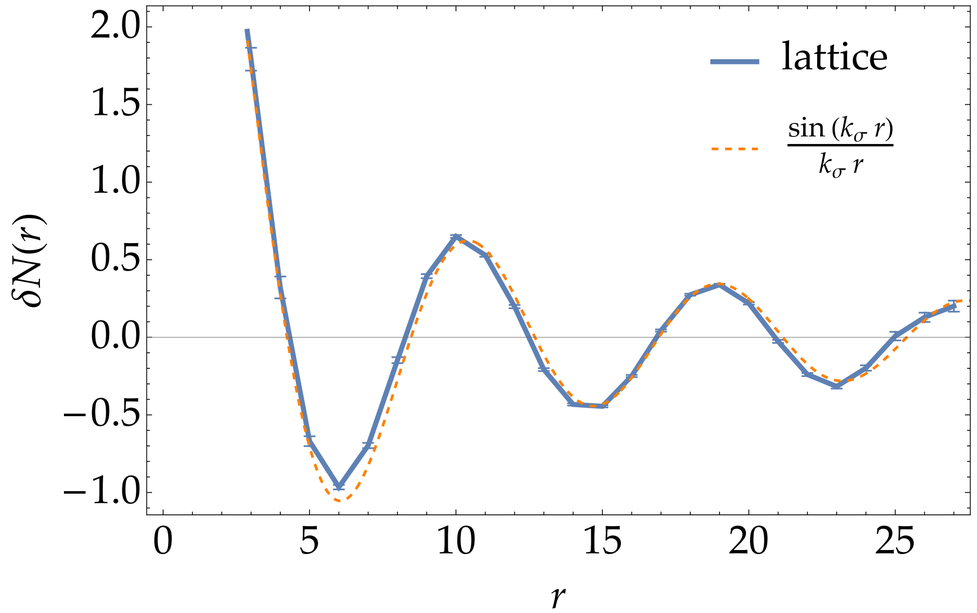
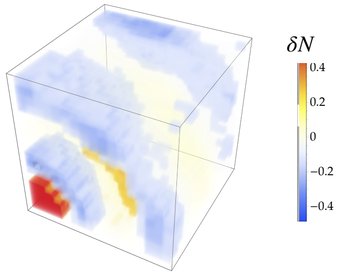
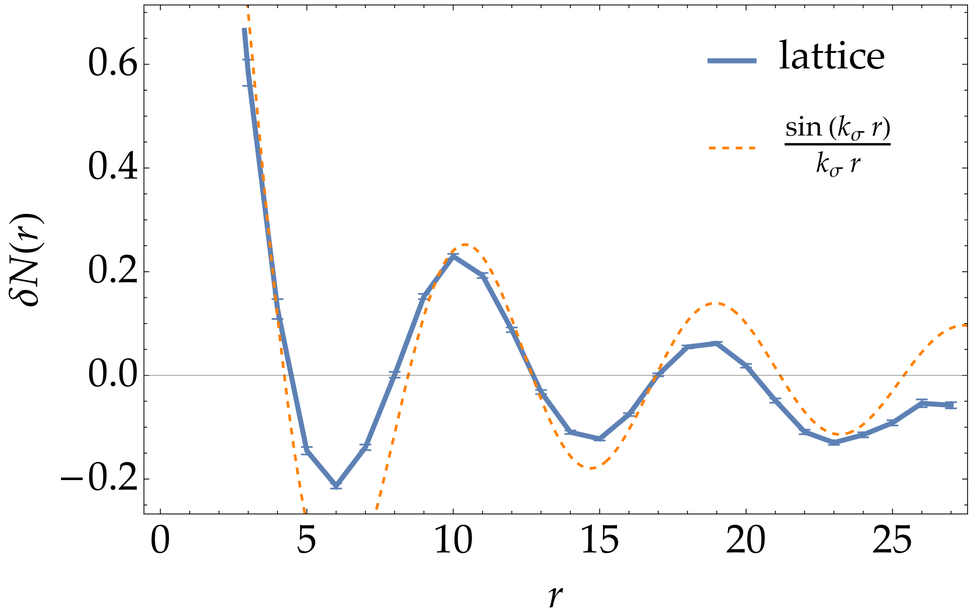


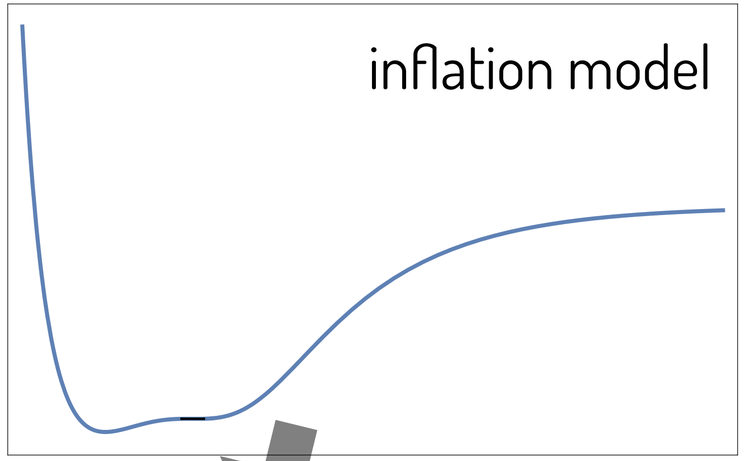


Ex. 2 : Inflection





Triangle study

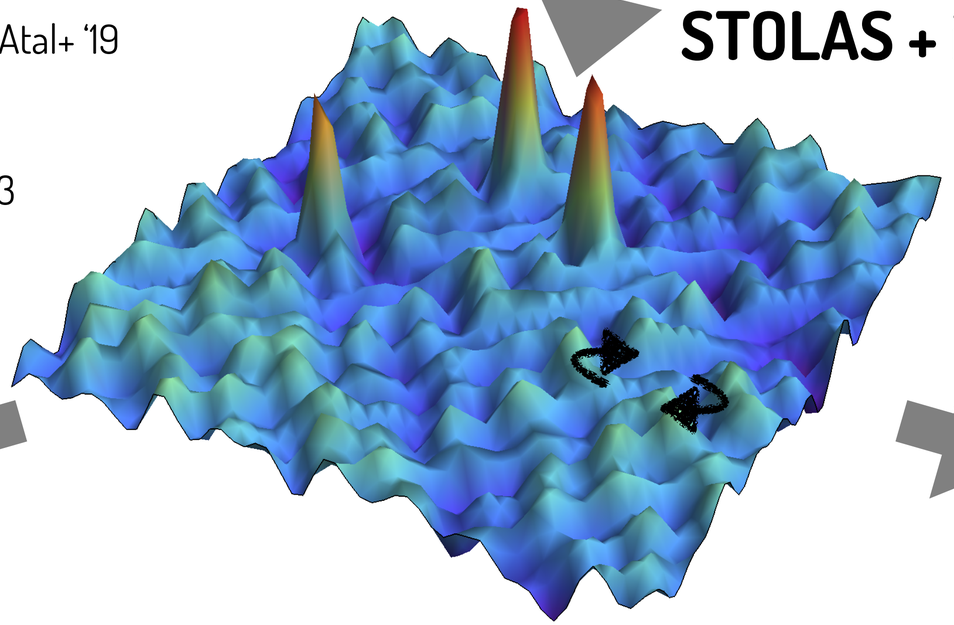


$$\mathscr{C}(r) = \frac{2}{3}\left[1 - (1 + r\zeta'(r))^2\right]$$

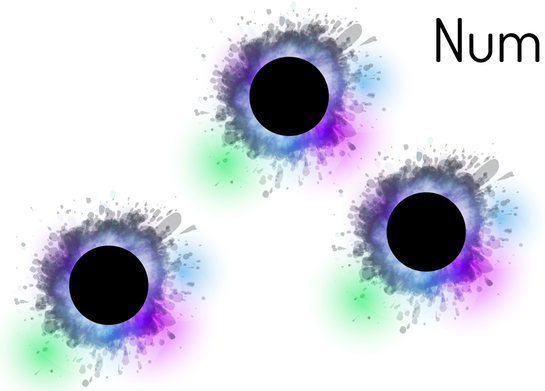
$$\bar{\mathscr{C}} = \frac{1}{V_{R_\mathrm{m}}}\int_0^{R_\mathrm{m}} 4\pi R^2 \mathscr{C}\,\mathrm{d}R > \bar{\mathscr{C}}_\mathrm{th} = \frac{2}{5}$$ Atal+ '19

$$M \sim M_{R_\mathrm{m}}(\bar{\mathscr{C}} - \bar{\mathscr{C}}_\mathrm{th})^{0.36}$$ Choptuik+ '93

STOLAS + importance sampling



Num. Rel.



PBH abundance

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

Ω_GW

induced GW b.g.

indirect evidence

4. 最近の話

Pulsar Timing Array

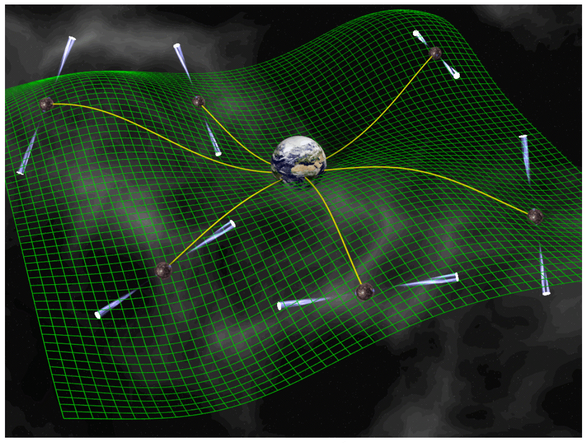
Draft version June 29, 2023
Typeset using LaTeX **twocolumn** style in AASTeX63

4重極ゆらぎ

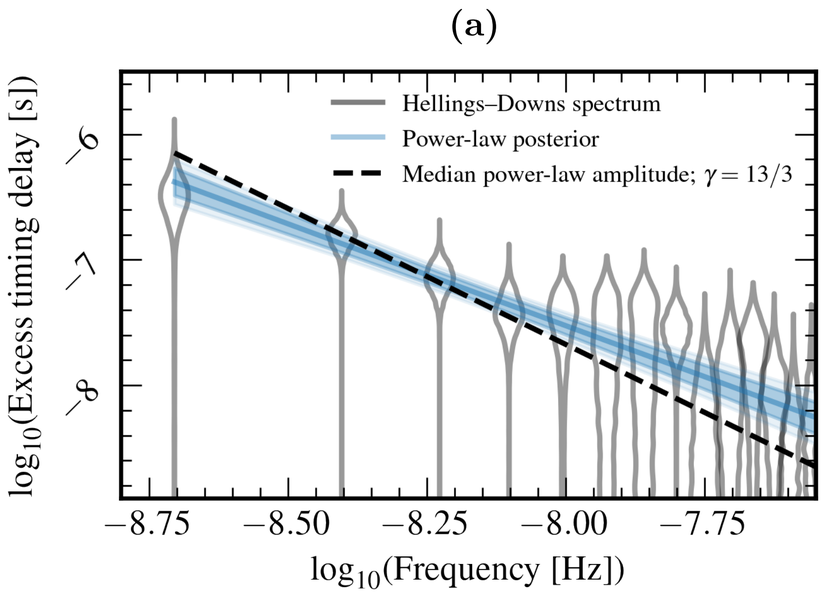
2306.16213

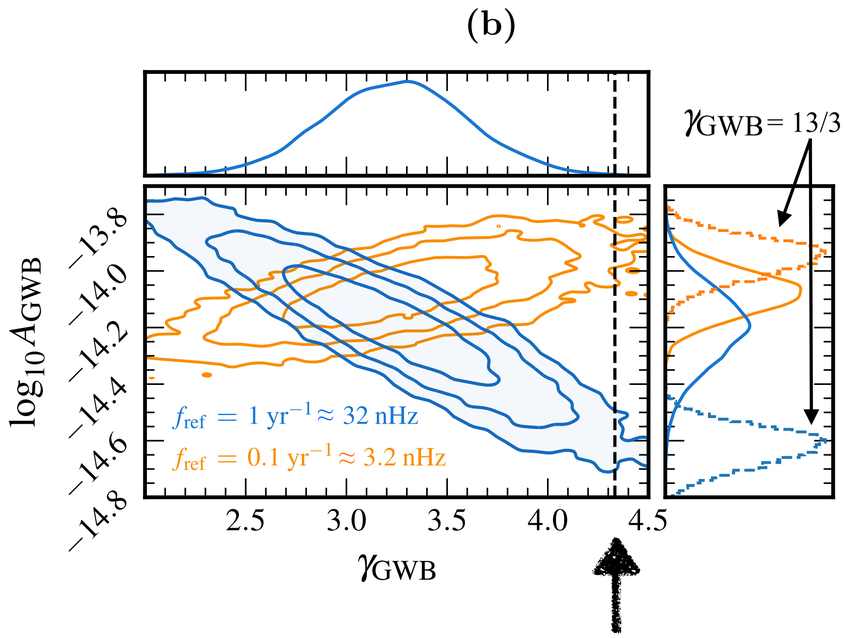
The NANOGrav 15-year Data Set: Evidence for a Gravitational-Wave Background

cf. European, Parkes (Australia), Chinese



~ nHz (~ yr^{-1}) 背景重力波





Supermassive BH binary

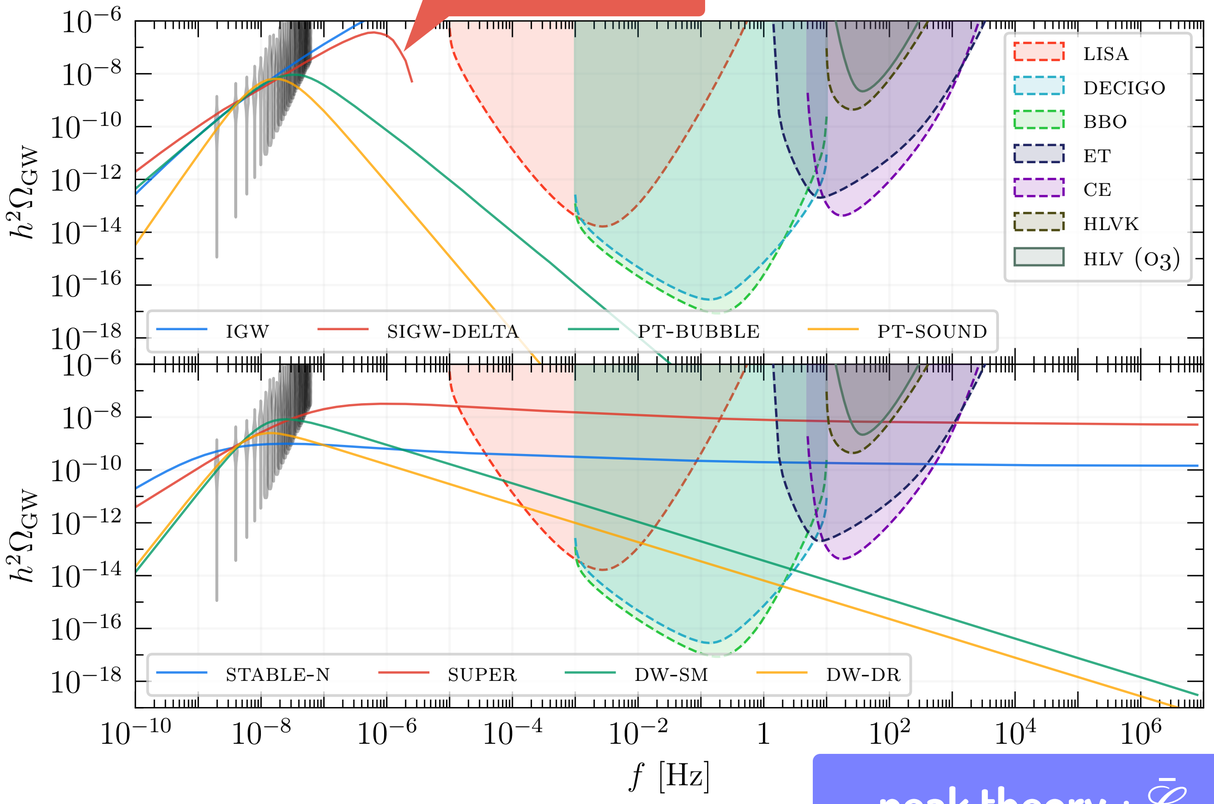
Pulsar Timing Array

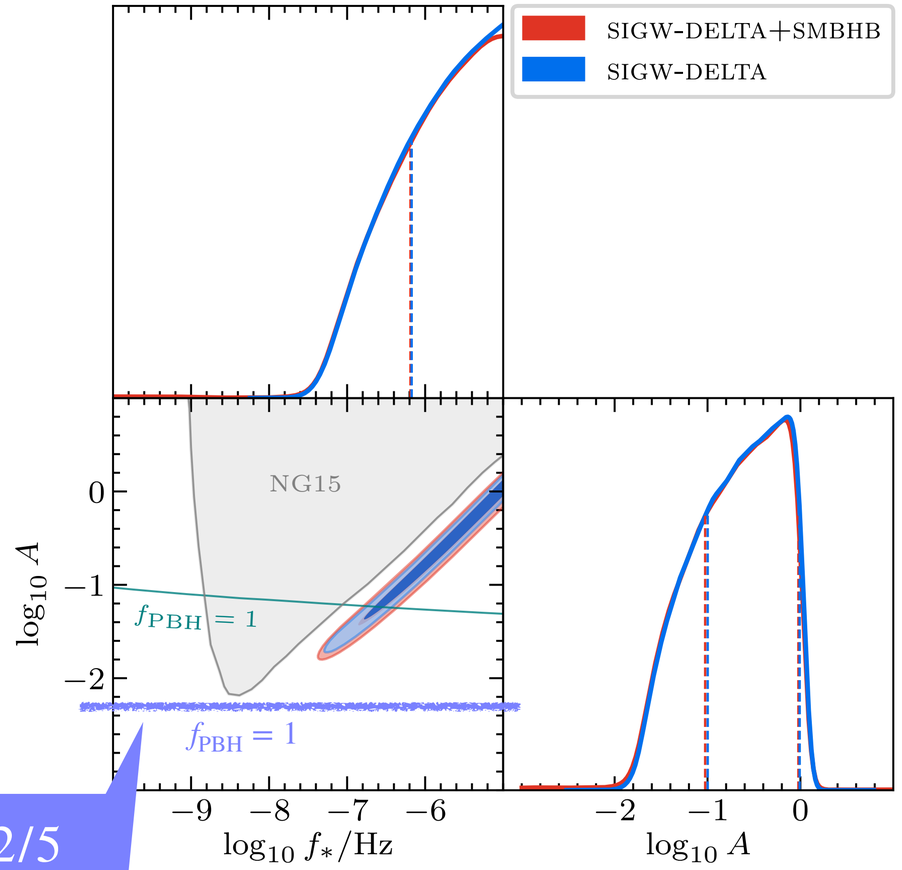
2306.16219

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

cf. Terada-san's poster, Lee-san's talk

誘導重力波





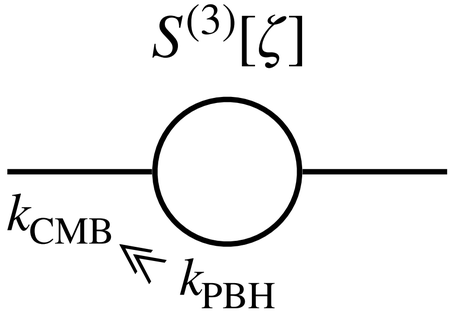
peak theory + $\bar{\mathscr{C}}_{\rm th} = 2/5$
(cf. Kitajima, YT, Yokoyama, Yoo '21)

One-loop on CMB

2211.03395

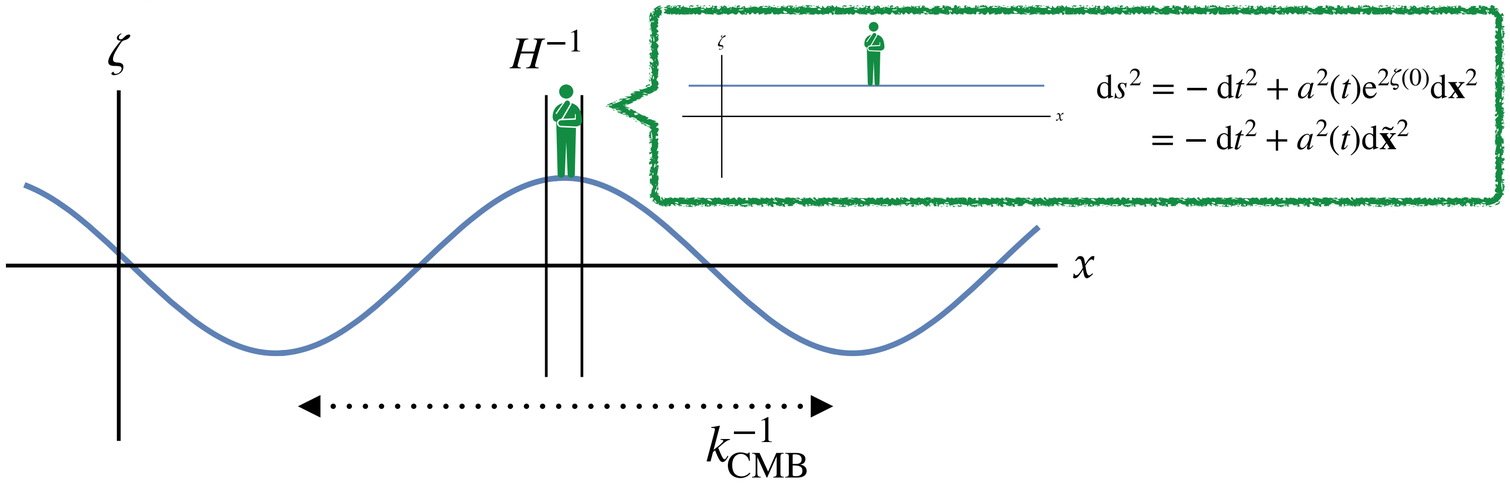
Ruling Out Primordial Black Hole Formation From Single-Field Inflation

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



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

Separate U. assumption



- ζ は漸近 dilatation の NG boson
  (cf. Sugishita-san's talk)
- (古典的に) soft ζ は保存量
  (Lyth, Malik, Sasaki '05)
- Maldacena's consistency relation ('03)

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

座標再定義の分のみ

Loop Cancellation

tensor ver. (Ota, Sasaki, Wang '22 x 2) は消えなかった……

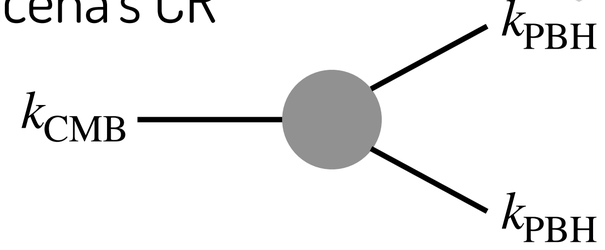
YT, Terada, Tokuda '23

KY

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

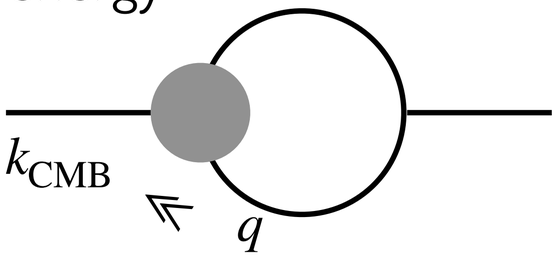
cf. Arroja & Tanaka '11

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



$$\propto \mathcal{P}_\zeta(k_{\rm CMB}) \int \mathrm{d}\ln q \frac{\mathrm{d}\mathcal{P}_\zeta(q)}{\mathrm{d}\ln \mathrm{q}} = \mathcal{P}_\zeta(k_{\rm CMB}) \Big(\mathcal{P}_\zeta(k \to \infty) - \mathcal{P}_\zeta(k \overset{10^{-9}}{\sim} k_{\rm CMB}) \Big)$$

$i\varepsilon$処方

漸近 dilatation による WT

tree ζ の保存 ⇔ Maldacena's CR ⇔ self-energy の cancel

まとめ

原始ブラックホールの直接的/間接的証拠はまだないが
見つかったら一発大逆転なので注視しよう