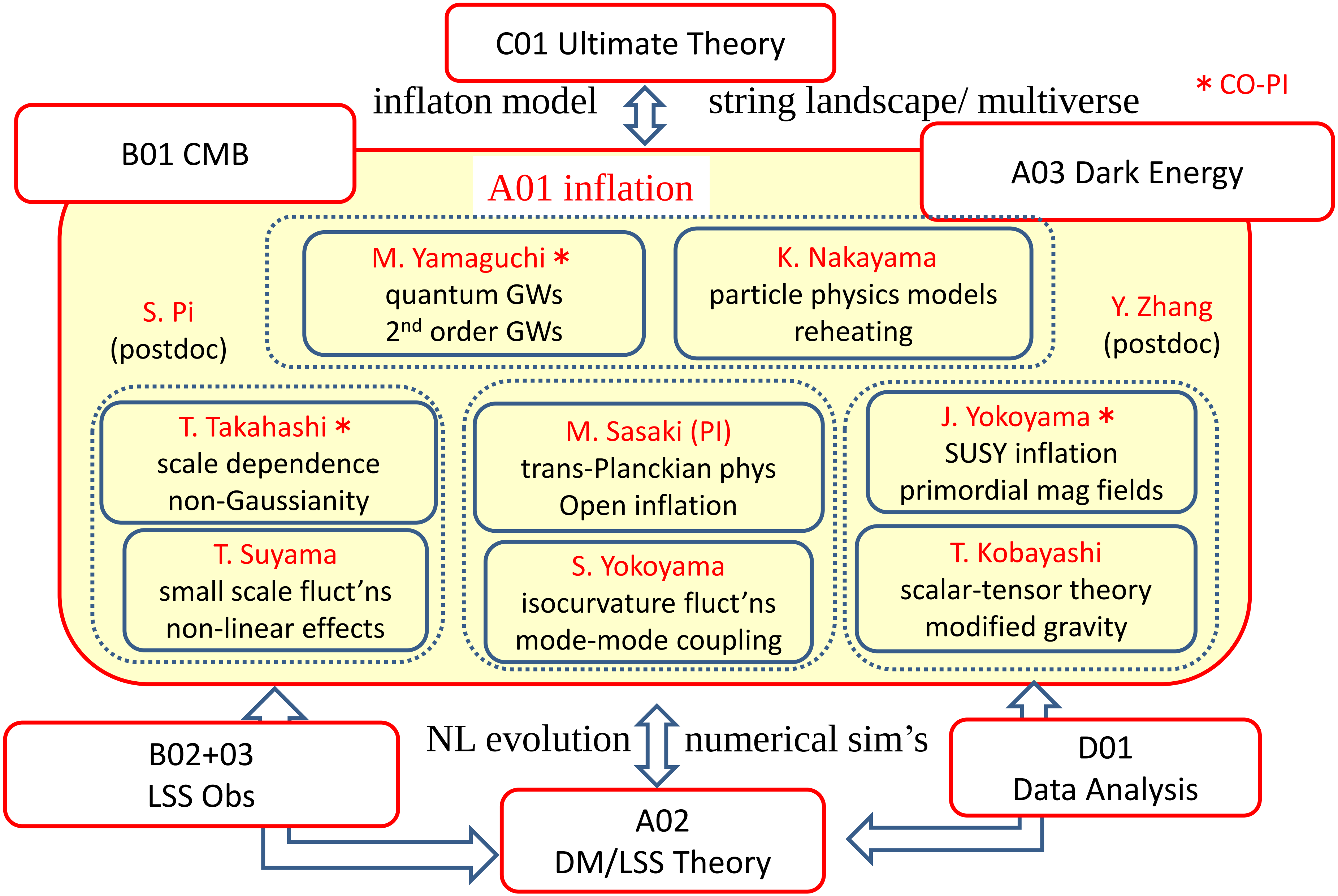
A01 (inflation) update

Misao Sasaki

17 February, 2020

A01 organization



Publications

2019 – today: 33 (published: 18)

total: 150 (published: 129); citation #=2200

1) Detecting Light Boson Dark Matter through Conversion into Magnon
By So Chigusa, Takeo Moroi, Kazunori Nakayama.
arXiv:2001.10666 [hep-ph].

2) Exploring Primordial Black Holes from Multiverse with Optical Telescopes
By Alexander Kusenko, Misao Sasaki, Sunao Sugiyama, Masahiro Takada, Volodymyr Takhistov, Edoardo Vitagliano.
arXiv:2001.09160 [astro-ph.CO].

3) Generalized ghost-free propagators in nonlocal field theory
By Luca Buoninfante, Gaetano Lambiase, Yuichi Miyashita, Wataru Takebe, Masahide Yamaguchi.
arXiv:2001.07830 [hep-th].

later in this talk

4) Quantum Ostrogradsky theorem
By Hayato Motohashi, Teruaki Suyama.
arXiv:2001.02483 [hep-th].

5) A novel formulation of the PBH mass function
By Teruaki Suyama, Shuichiro Yokoyama.
arXiv:1912.04687 [astro-ph.CO].

T Suyama's talk

6) Could the Black Hole Singularity be a Field Singularity?
By Guillem Domènech, Atsushi Naruko, Misao Sasaki, Christof Wetterich.
arXiv:1912.02845 [gr-qc].

7) Signals of Axion Like Dark Matter in Time Dependent Polarization of Light
By So Chigusa, Takeo Moroi, Kazunori Nakayama.
arXiv:1911.09850 [astro-ph.CO].

red = A01

Green = B03

8) Probing Small Scale Primordial Power Spectrum with 21cm Line Global Signal
By Shintaro Yoshiura, Keitaro Takahashi, Tomo Takahashi.
arXiv:1911.07442 [astro-ph.CO].

9) Gravitational leptogenesis with kination and gravitational reheating
By Kohei Kamada, Jun'ya Kume, Yusuke Yamada, Jun'ichi Yokoyama.
arXiv:1911.02657 [hep-ph]. JCAP 2001 (2020) no.01, 016.

later in this talk

10) Effective Field Theory of Anisotropic Inflation and Beyond
By Jinn-Ouk Gong, Toshifumi Noumi, Gary Shiu, Jiro Soda, Kazufumi Takahashi, Masahide Yamaguchi.
arXiv:1910.11533 [hep-th].

11) Universal Upper Bound on the Inflationary Energy Scale from the Trans-Planckian Censorship Conjecture
By Shuntaro Mizuno, Shinji Mukohyama, Shi Pi, Yun-Long Zhang.
arXiv:1910.02979 [astro-ph.CO].

12) Universal infrared scaling of gravitational wave background spectra
By Rong-Gen Cai, Shi Pi, Misao Sasaki.
arXiv:1909.13728 [astro-ph.CO].

later in this talk

13) Vacuum decays around spinning black holes
By Naritaka Oshita, Kazushige Ueda, Masahide Yamaguchi.
arXiv:1909.01378 [hep-th]. JHEP 2001 (2020) 015.

14) Redshift space distortions in the presence of non-minimally coupled dark matter
By Fabio Chibana, Rampei Kimura, Masahide Yamaguchi, Daisuke Yamauchi, Shuichiro Yokoyama.
arXiv:1908.07173 [astro-ph.CO]. JCAP 1910 (2019) no.10, 049.

15) Analytic Description of Primordial Black Hole Formation from Scalar Field Fragmentation
By Eric Cotner, Alexander Kusenko, Misao Sasaki, Volodymyr Takhistov.
arXiv:1907.10613 [astro-ph.CO]. JCAP 1910 (2019) no.10, 077.

16) Pulsar Timing Array Constraints on the Induced Gravitational Waves
By Rong-Gen Cai, Shi Pi, Shao-Jiang Wang, Xing-Yu Yang.
arXiv:1907.06372 [astro-ph.CO]. JCAP 1910 (2019) no.10, 059.

red = A01

cyan = D1

blue = C01

17) Vector Coherent Oscillation Dark Matter
By Kazunori Nakayama.
arXiv:1907.06243 [hep-ph]. JCAP 1910 (2019) no.10, 019.

18) Horndeski model in nonlinearly realized supergravity
By Yusuke Yamada, Jun'ichi Yokoyama.
arXiv:1906.11430 [hep-th]. JHEP 1912 (2019) 041.

later in this talk

19) Constraints on decaying dark matter from weak lensing and cluster counts
By Kari Enqvist, Seshadri Nadathur, Toyokazu Sekiguchi, Tomo Takahashi.
arXiv:1906.09112 [astro-ph.CO].

20) Abundance of primordial black holes with local non-Gaussianity in peak theory
By Chul-Moon Yoo, Jinn-Ouk Gong, Shuichiro Yokoyama.
arXiv:1906.06790 [astro-ph.CO]. JCAP 1909 (2019) no.09, 033.

S Yokoyama's talk

21) Clustering of primordial black holes with non-Gaussian initial fluctuations
By Teruaki Suyama, Shuichiro Yokoyama.
arXiv:1906.04958 [astro-ph.CO]. PTEP 2019 (2019) no.10, 103E02.

22) Structure Formation with Two Periods of Inflation: Beyond PLaIn Lambda CDM
By Kari Enqvist, Till Sawala, Tomo Takahashi.
arXiv:1905.13580 [astro-ph.CO].

23) Novel Flavon Stabilization with Trimaximal Neutrino Mixing
By So Chigusa, Shinta Kasuya, Kazunori Nakayama.
arXiv:1905.11517 [hep-ph]. Phys.Rev. D100 (2019) no.1, 015030.

24) Hyperbolic field space and swampland conjecture for DBI scalar
By Shuntaro Mizuno, Shinji Mukohyama, Shi Pi, Yun-Long Zhang.
arXiv:1905.10950 [hep-th]. JCAP 1909 (2019) no.09, 072.

25) A Note on Gravitational Particle Production in Supergravity
By Kazunori Nakayama.
arXiv:1905.09143 [hep-ph]. Phys.Lett. B797 (2019) 134857.

red = A01

26) A novel constraint on the Primordial Magnetic Fields using 21-cm line absorption signal
By Teppei Minoda, Hiroyuki Tashiro, Tomo Takahashi.
PoS KMI2019 (2019) 028.

27) Primordial black hole tower: Dark matter, earth-mass, and LIGO black holes
By Yuichiro Tada, Shuichiro Yokoyama.
arXiv:1904.10298 [astro-ph.CO]. Phys.Rev. D100 (2019) no.2, 023537.

red = A01

Green = B03

28) Secondary CMB temperature anisotropies from magnetic reheating
By Shohei Saga, Atsuhisa Ota, Hiroyuki Tashiro, Shuichiro Yokoyama.
arXiv:1904.09121 [astro-ph.CO]. Mon.Not.Roy.Astron.Soc. 490 (2019) no.3, 4419-4427.

29) Primordial Tensor Perturbation in Double Inflationary Scenario with a Break
By Shi Pi, Misao Sasaki, Ying-li Zhang.
arXiv:1904.06304 [gr-qc]. JCAP 1906 (2019) 049.

30) Possible resolution of a spacetime singularity with field transformations
By Atsushi Naruko, Chul-Moon Yoo, Misao Sasaki.
arXiv:1903.10763 [gr-qc].

31) Screening mechanism in degenerate higher-order scalar-tensor theories evading gravitational wave constraints
By Shin'ichi Hirano, Tsutomu Kobayashi, Daisuke Yamauchi.
arXiv:1903.08399 [gr-qc]. Phys.Rev. D99 (2019) no.10, 104073.

32) Constraining degenerate higher-order scalar-tensor theories with linear growth of matter density fluctuations
By Shin'ichi Hirano, Tsutomu Kobayashi, Daisuke Yamauchi, Shuichiro Yokoyama.
arXiv:1902.02946 [astro-ph.CO]. Phys.Rev. D99 (2019) no.10, 104051.

33) Smallest Halos in Thermal Wino Dark Matter
By Shin'ichiro Ando, Ayuki Kamada, Toyokazu Sekiguchi, Tomo Takahashi.
arXiv:1901.09992 [hep-ph]. Phys.Rev. D100 (2019) no.12, 123519.

later in this talk

34) Constraints on Earth-mass primordial black holes from OGLE 5-year microlensing events
By Hiroko Niikura, Masahiro Takada, Shuichiro Yokoyama, Takahiro Sumi, Shogo Masaki.
arXiv:1901.07120 [astro-ph.CO]. Phys.Rev. D99 (2019) no.8, 083503.

workshops

A1-C1 joint workshop on quantum entanglement in cosmology

21-22 May 2019 @ Kavli IPMU

Tuesday, 21 May

Andreas Albrecht
Decoherence and einselection in equilibrium in an adapted Caldeira Leggett model

Andrew Arrasmith
Looking for Scalar/Tensor Entanglement in the Initial State of Inflation

Yasunori Nomura (C1)
Quantum Mechanics of an Evaporating Black Hole

Kazuhiro Yamamoto (C1)
Vacuum state as entangled state between left, right, future and past

Sugumi Kanno
Non classical primordial gravitational waves (tentative)

Jinn-Ouk Gong
Quantum non-linear evolution of inflationary tensor perturbations

Wednesday, 22 May

~ 25 participants
very fruitful discussions

Shinji Mukohyama
Some thoughts on entropy bounds, swampland and inflation

Jerome Martin
Can we observe quantum entanglement in the CMB?

Mark Hertzberg
Some aspects of modeling quantum behaviour with classical simulations

Justin Khoury
Symmetries and Ward Identities in Cosmology

Junsei Tokuda
On the contribution of long-wavelength fluctuations to primordial perturbations via quantum interference

Misao Sasaki
Summary/discussion

Focus Week on Primordial Black Holes

2 – 6 December 2019 @ Kavli IPMU

Monday 02 December 2019 ....

Bernard Carr: PRIMORDIAL BLACK HOLES AS THE SOLUTION OF MANY COSMOLOGICAL CONUNDRA ....

Masahiro Takada: Constraining PBH with microlensing ....

Shi Pi: Universal infrared scaling of induced gravitational waves ....

IPMU Tea Time ....

Tuesday 03 December 2019 ....

Ruth Gregory: Primordial Black Holes and Higgs Vacuum Decay ....

Coffee break ....

Alexander Kusenko: PBH production via scalar field fragmentation ....

Group Photo ....

Lunch ....

Volodymyr Takhistov Gaining Insight into PBH Dark Matter with Compact Stars ....

George Fuller: Supermassive Stars and Black Hole Seeds: A narrow mass range with triple trouble; Dark Sector production of supermassive black hole seeds ....

Hayato Motohashi: Constant roll and primordial black holes ....

Teruaki Suyama: Clustering of primordial black holes with non-Gaussian initial fluctuations ....

Chulmoon Yoo: Abundance of primordial black holes with local non-Gaussianity in peak theory ....

~ 35 participants
lots of interesting ideas

Wednesday 04 December 2019 ....

Edoardo Vitagliano: Exploring Primordial Black Holes from Multiverse with Optical Telescopes ....

Kazunori Kohri: Formations and evolutions of PBHs in the matter-dominated Universe ....

Chris Byrnes: Determining the origin of LIGO's merging black holes ....

Cristiano Germani : Universal threshold and non-linear PBHs statistics ....

Tomohiro Harada: Effect of Inhomogeneity on Primordial Black Hole Formation in the Matter Dominated Era ......

Thursday 05 December 2019 ....

Masahiro Kawasaki : Particle physics models for primordial black hole formation ....

Alexander Dolgov: Astronomical data in favor of abundant population of PBH in the universe and the mechanism of their formation. ....

Antonio Riotto: Primordial Black Holes and Gravitational Waves ..

Alexandros Kehagias: Unstable modes in Kerr Black Holes ....

Minxi He: On the formation threshold of rotating primordial black h

Friday 06 December 2019 ....

Savvas Koushiappas: Detecting primordial black holes ....

Misao Sasaki: TBA ....

Yuichiro Tada: Primordial black hole tower: Dark matter, earth-mass, and LIGO black holes ....

Anand Hedge: Gravitational Thomas Precession: New Window to Study PBHs ....

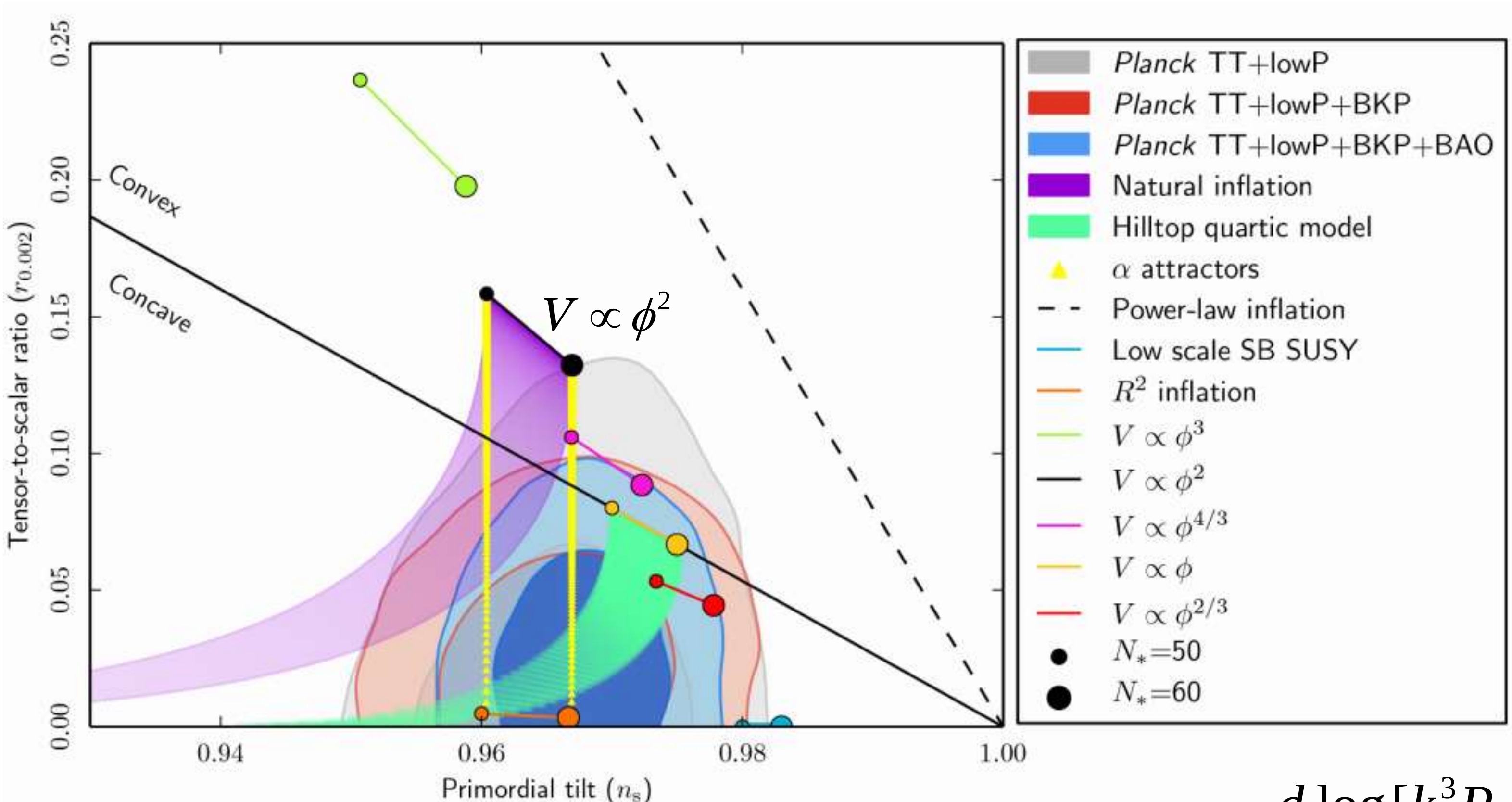
Yi-Peng Wu: Statistical bias for black hole mass functions from the inflationary power spectrum ....

Round table discussion ....

Inflation
Current Status

Planck constraints on inflation

Planck 2015 (2018)XX



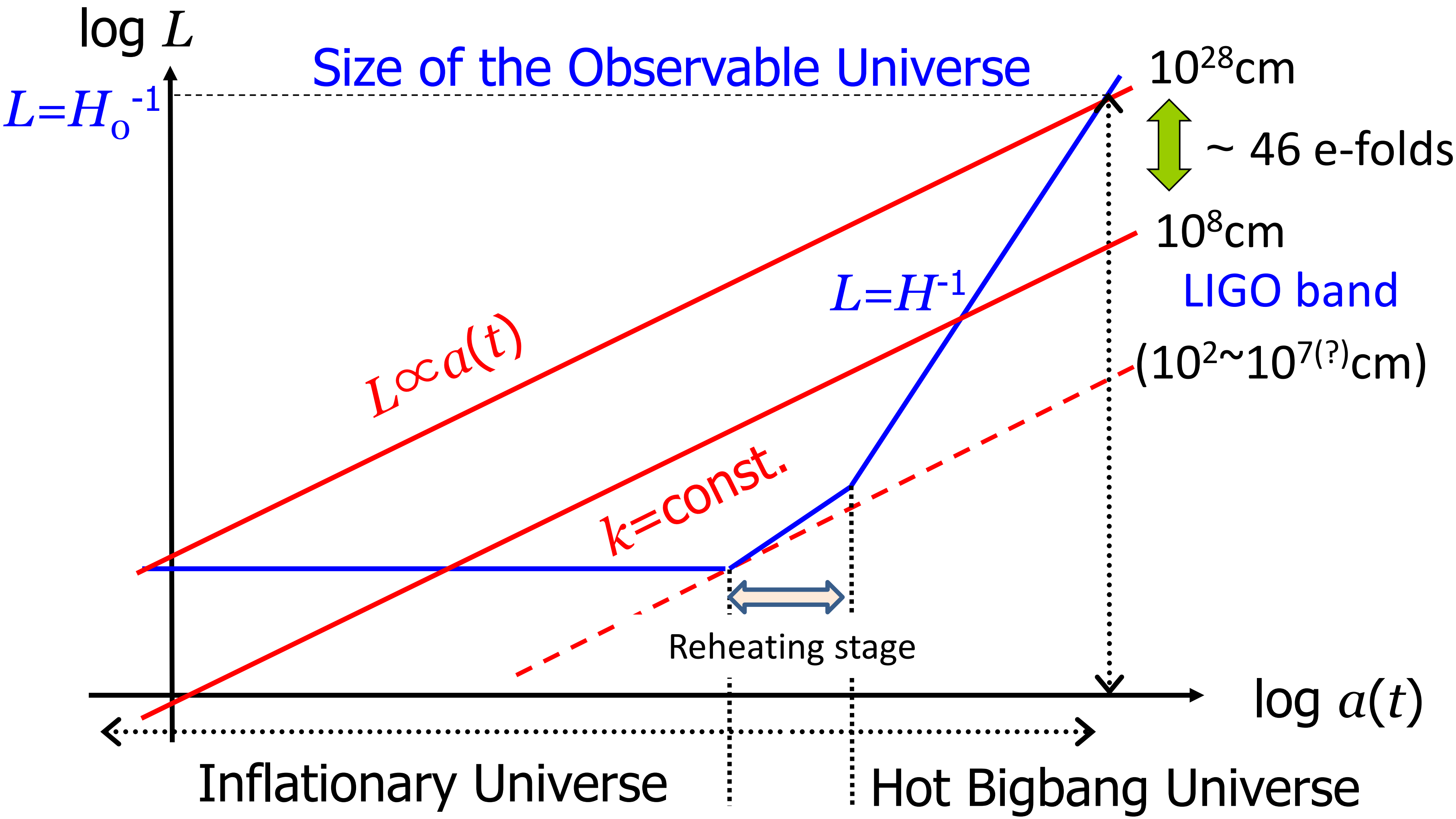
- scalar spectral index: $n_s \sim 0.96$
- tensor-to-scalar ratio: $r < 0.1$ (95%CL)
- simplest $V \propto \phi^2$ model excluded

$$n_s - 1 \equiv \frac{d \log[k^3 P_S(k)]}{d \log k}$$

$$r \equiv \frac{P_T(k)}{P_S(k)}$$

length scales of the inflationary universe

⇔ targets for multi-frequency GW cosmology



Selected Papers by A01 members

Realization of the Generalized G-Inflation in Supergravity

Jun'ichi Yokoyama

$$\mathcal{L}_2 = K(\phi, X)$$
$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi$$
$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$
$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5X}\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]$$

Y. Yamada & JY JHEP1912(2019)041

This well-known theory can be constructed from nonlinearly realized supersymmetry from

$$\mathcal{F}_2 = P(\mathcal{X}, \hat{\phi}),$$
$$\mathcal{F}_3 = -G_3(\mathcal{X}, \hat{\phi})(\mathcal{D}^a\mathcal{D}_a\hat{\phi}),$$
$$\mathcal{F}_4 = G_4(\mathcal{X}, \hat{\phi})\hat{\mathcal{R}}_s + G_{4\mathcal{X}}[(\mathcal{D}^a\mathcal{D}_a\hat{\phi})^2 - (\mathcal{D}_a\mathcal{D}_b\hat{\phi})^2]$$
$$\mathcal{F}_5 = G_5(\mathcal{X}, \hat{\phi})\hat{\mathcal{G}}^{ab}\mathcal{D}_a\mathcal{D}_b\hat{\phi} - \frac{1}{6}G_{5\mathcal{X}}(\mathcal{X}, \hat{\phi})[(\mathcal{D}^a\mathcal{D}_a\hat{\phi})^3 - 3(\mathcal{D}^a\mathcal{D}_a\hat{\phi})(\mathcal{D}_b\mathcal{D}_c\hat{\phi})^2 + 2(\mathcal{D}_a\mathcal{D}_b\hat{\phi})^3]$$

$$\hat{\phi} = \tfrac{1}{2}(\Phi + \bar{\Phi}), \quad \mathcal{X} = -\tfrac{1}{2}\mathcal{D}_a\hat{\phi}\mathcal{D}^a\hat{\phi}$$

with $S(\Phi - \bar{\Phi}) = 0$, where $S(x, \theta)$ is a ninlpotent superfield satisfying $S^2(x, \theta) = 0$.

This allows construction of varieties of inflation models in supergravity, including those which are followed by a kination regime with gravitational reheating.

$$\begin{aligned}\mathcal{L} = &\int d^4\theta E \frac{16S\bar{S}}{\mathcal{D}^\alpha\mathcal{D}_\alpha S\bar{\mathcal{D}}_{\dot{\alpha}}\bar{\mathcal{D}}^{\dot{\alpha}}\bar{S}}\sum_{i=2}^{5}\mathcal{F}_i \\ = &P(X, \phi) - G_3(X, \phi)\nabla^2\phi + G_4(X, \phi)\hat{R} \\ &+ G_{4X}[(\nabla^2\phi)^2 - (\nabla_m\nabla_n\phi)^2] + G_5(X, \phi)\hat{G}^{mn}\nabla_m\nabla_n\phi \\ &- \frac{1}{6}G_{5X}[(\nabla^2\phi)^3 - 3(\nabla^2\phi)(\nabla_m\nabla_n\phi)^2 + 2(\nabla_m\nabla_n\phi)^3],\end{aligned}$$

Gravitational leptogenesis with kination and gravitational reheating

Jun'ichi Yokoyama

K.Kamada, J.Kume, Y.Yamada & JY JCAP 2001 (2020) 016

$$\frac{M_{\rm Pl}^2}{2}R + \frac{M_{\rm Pl}^2}{4}f(\phi)R\tilde{R} + \mathcal{L}_\phi$$

Chiral gravitational waves are generated and affect the nonconservation of lepton number through gravitational anomaly

$$\nabla_\mu J_L^\mu = \frac{N_{\rm R-L}}{24(4\pi)^2}R\tilde{R}$$

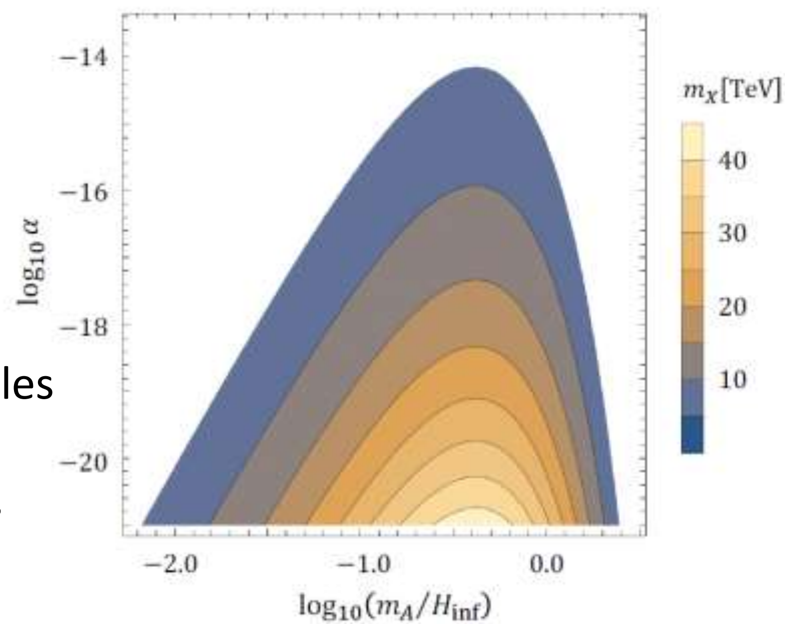
Models with standard reheating cannot explain adequate baryon asymmetry while those with gravitational-reheating in kination can due to the smallness of the created entropy.

☆Gravitational particle creation for dark matter and reheating

S. Hashiba & JY Phys.Rev. D99 (2019)043008

Inflation followed by kination: reheating proceeds through gravitational particle production of A particles and their subsequent decay. X particles, which are also created gravitationally, are supposed to be DM.

$\Gamma = \alpha m_A$ quantifies decay rate of A.



Masahide Yamaguchi

Identification of the origin of cosmic acceleration

We have almost confirmed the presence of inflation and dark energy, but, unfortunately, we know neither the identification of an inflaton nor that of dark energy.

Identification methods

- **Top down approach :**

  To construct the unique model from the ultimate theory like string theory. (-> C1)

- **Bottom up approach**

  To consider the most general model. Then, we can constrain models (or single out the true model finally) from the observational results.

In this bottom up approach, we have proposed a class of nonlocal theory and spatially covariant theory as general models, in which an invertible field transformation is quite useful to classify these models.

Masahide Yamaguchi

Invertible field transformations with derivatives: necessary and sufficient conditions

Eugeny Babichev, Keisuke Izumi, Norihiro Tanahashi, Masahide Yamaguchi, arXiv:1907.12333

Field transformation is ubiquitous in physics and mathematics.
But, as far as we know, nobody has yet given the necessary and sufficient conditions for invertible field transformation with derivatives !!

As a simplest example : $\phi_i = \phi_i(\psi_a, \partial_\mu \psi_a) \quad (i, a = 1, 2).$

Two fields with up to first order derivatives

By using the technique of characteristics, the necessary and sufficient conditions for the invertibility are given by

Two useful matrices: $A^\mu_{ia} \equiv \dfrac{\partial \phi_i}{\partial(\partial_\mu \psi_a)}, \quad B_{ia} \equiv \dfrac{\partial \phi_i}{\partial \psi_a}.$ (At least, one of A matrices is non-zero).

$$\begin{cases} (1)\ A^\mu_{ia} = a^\mu V_i U_a \quad (V_i V_i = 1, \quad U_a U_a = 1) & \text{(A can be decomposed this way)} \\ (2)\ n_i B_{ia} m_a = 0 & \left(n_i := \epsilon_{ij} V_j, \quad m_a := \epsilon_{ab} U_b\right) \\ (3)\ n_i B_{ia} U_a \neq 0, \quad (V_i B_{ia} - a^\mu \partial_\mu U_a)\, m_a \neq 0 & \end{cases}$$

Vector coherent oscillation

Kazunori Nakayama

KN (2019)
(c.f. string theory)

P.Arias et al. (2012)

- Hidden photon is a dark matter candidate
- Coherent oscillation as light vector dark matter

$$\mathcal{L} = \frac{1}{2}\xi R\, g^{MN} A_M A_N \qquad \xi = \frac{1}{6} \longrightarrow \text{coherent oscillation}$$

- However, it suffers ghost instability for longitudinal mode
- Modified model for vector coherent oscillation: KN (2019)

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{4} f^2(\phi) g^{MN} g^{KL} \mathcal{F}_{MK} \mathcal{F}_{NL} - \frac{1}{2} m^2 g^{MN} \mathcal{A}_M \mathcal{A}_N \right)$$

First successful model of vector coherent oscillation dark matter!

- Possible observational signature:

Statistical anisotropy in CDM isocurvature perturbation

Tomo Takahashi

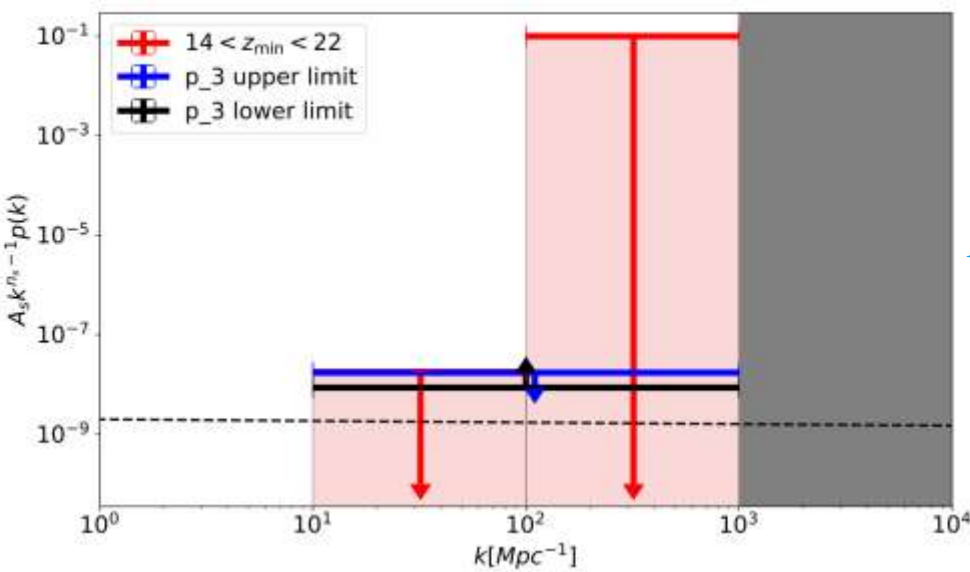
Constraints on small-scale primordial power spectrum from 21cm global signal

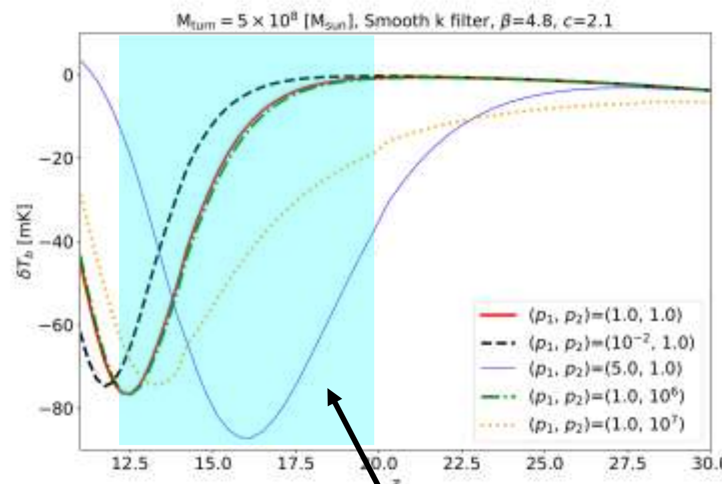
[S.Yoshiura, K.Takahashi, T.Takahashi 1911.07442]

(For constraints on the runnings, [S.Yoshiura, K.Takahashi, T.Takahashi 1805.11806])

- The information on the position (redshift) of the absorption trough of 21cm global signal can give upper and even lower bounds on small-scale primordial power spectrum.

(NB: we also need to constrain astrophysics parameters.)





Range of absorption trough observed by EDGES

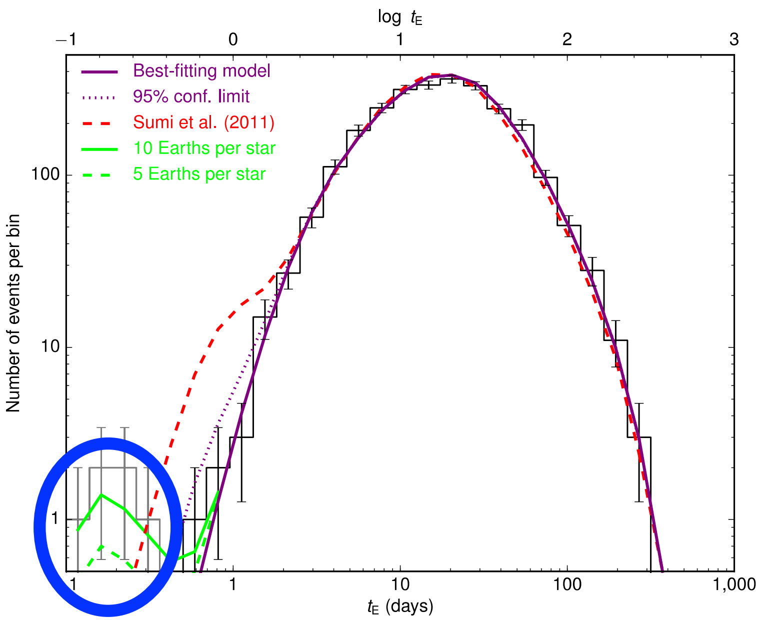
(As an illustration purpose, we used EDGES results to obtain the constraint.)

Shuichiro Yokoyama

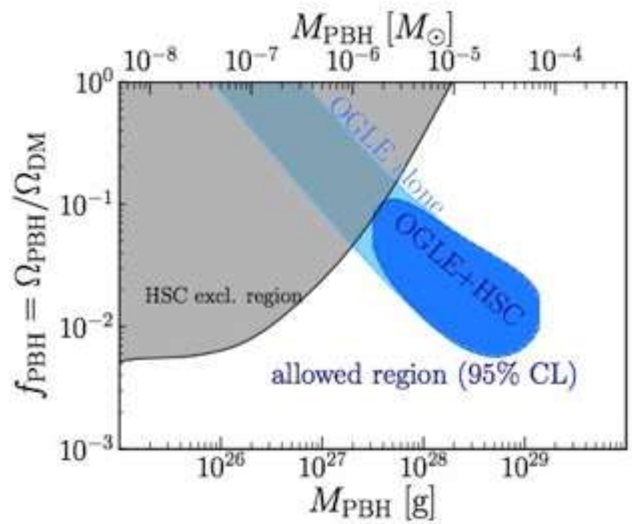
Earth mass primordial black holes?

Niikura, Takada, Yokoyama + (2019)
Tada, Yokoyama (2019)
(B03との共同研究，公募研究18H04356)

Mroz et al. arXiv:1707.07634



OGLE-IV reported 6 microlensing events with ultra short-time scale



➔ detection of earth mass PBHs?

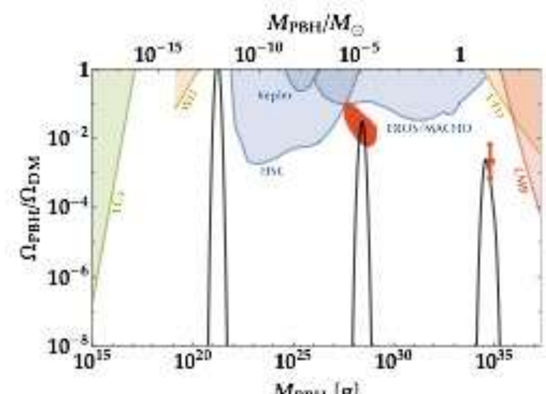
Niikura+ Phys.Rev. D99 (2019) no.8, 083503

➔ PBHs with 3-generations? (DM, LIGO-BHs, and earth mass..)

➔ Multi-phase inflation?

$$V(\phi) = \sum_{i=1,2,3,4} V_{{\rm hill},i}(\phi_i) + \sum_{i\neq j} \frac{1}{2} c_{ij} V_{{\rm hill},i}(\phi_i) \frac{\phi_j^2}{M_{\rm Pl}^2}.$$

$$V_{{\rm hill},i}(\phi_i) = \left(v_i^2 - g_i \frac{\phi_i^n}{M_{\rm Pl}^{n-2}}\right)^2 - \frac{1}{2}\kappa_i v_i^4 \frac{\phi_i^2}{M_{\rm Pl}^2} - \varepsilon_i v_i^4 \frac{\phi_i}{M_{\rm Pl}}$$



Tada, Yokoyama Phys.Rev. D100 (2019) no.2, 023537

PBHs
from Inflation

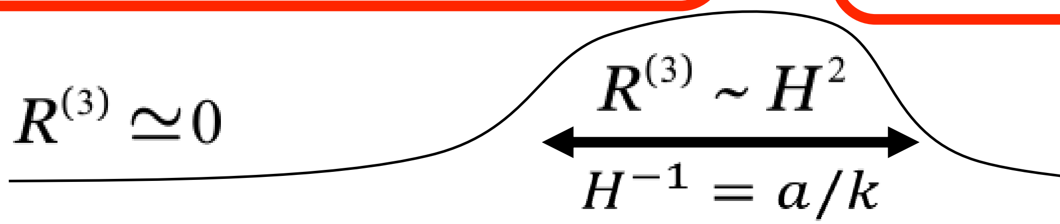
Curvature perturbation to PBH

- gradient expansion/separate universe approach

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

Hamiltonian constraint (Friedmann eq.)

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



formation of a closed universe

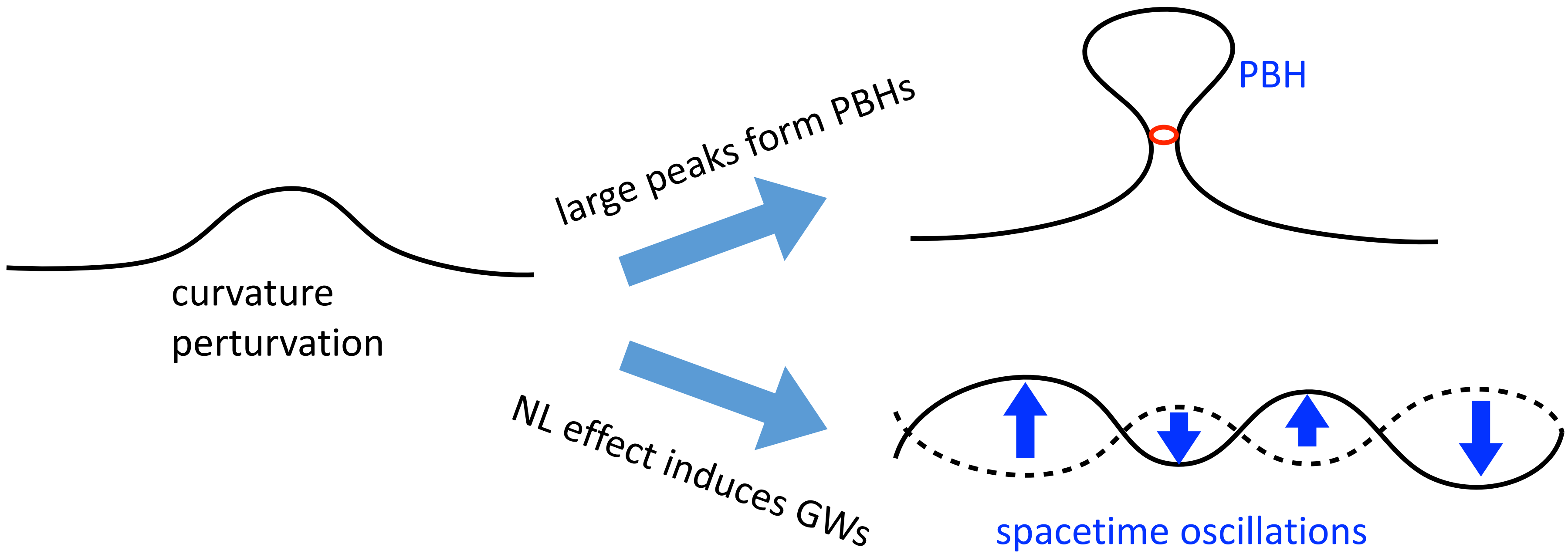
- If $R^{(3)} \sim H^2$ $\left(\Leftrightarrow \delta\rho_c/\rho \sim 1\right)$, it collapses to form BH

Young, Byrnes & MS '14

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

- Spins of PBHs are expected to be very small

GWs can capture PBHs!



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

Background GWs
at LISA band

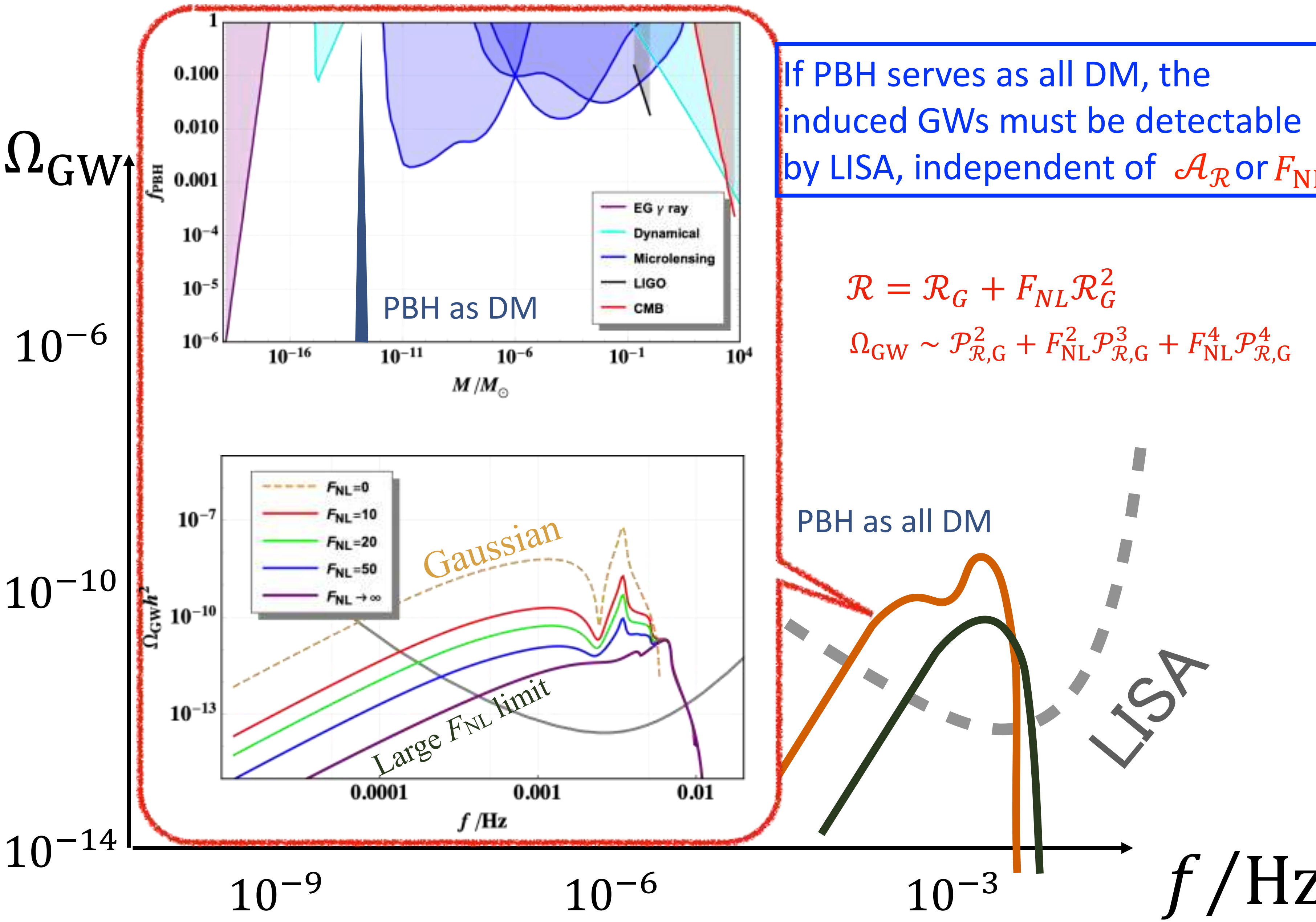
LIGO-Virgo :10 - 1000 Hz

[Cai, SP, and Sasaki, PRL122, 201101]

If PBH serves as all DM, the induced GWs must be detectable by LISA, independent of $\mathcal{A}_{\mathcal{R}}$ or $F_{\rm NL}$

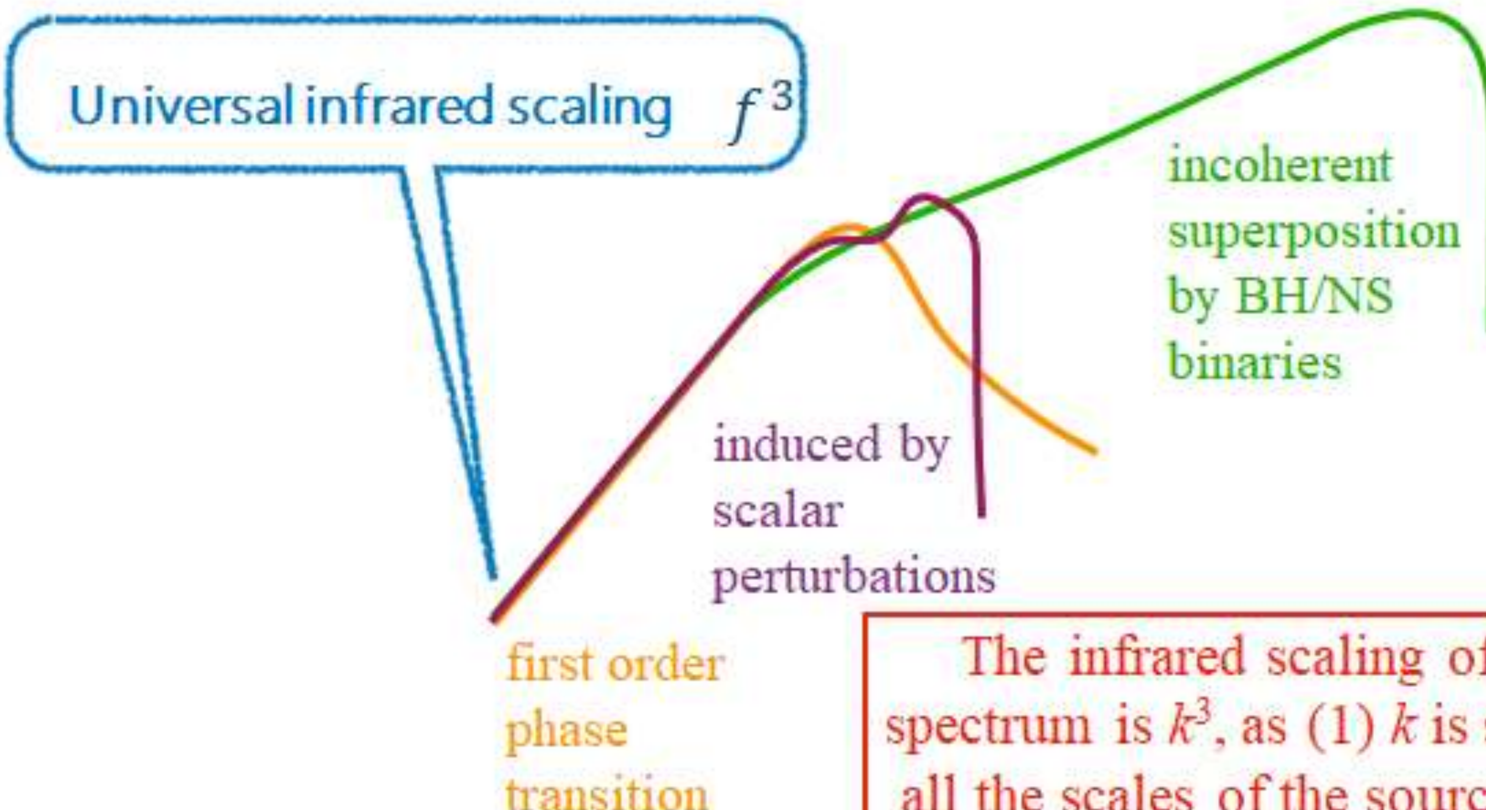
$$\mathcal{R} = \mathcal{R}_G + F_{NL}\mathcal{R}_G^2$$

$$\Omega_{\rm GW} \sim \mathcal{P}_{\mathcal{R},\rm G}^2 + F_{\rm NL}^2\mathcal{P}_{\mathcal{R},\rm G}^3 + F_{\rm NL}^4\mathcal{P}_{\mathcal{R},\rm G}^4$$



Infrared Scaling of SGWB

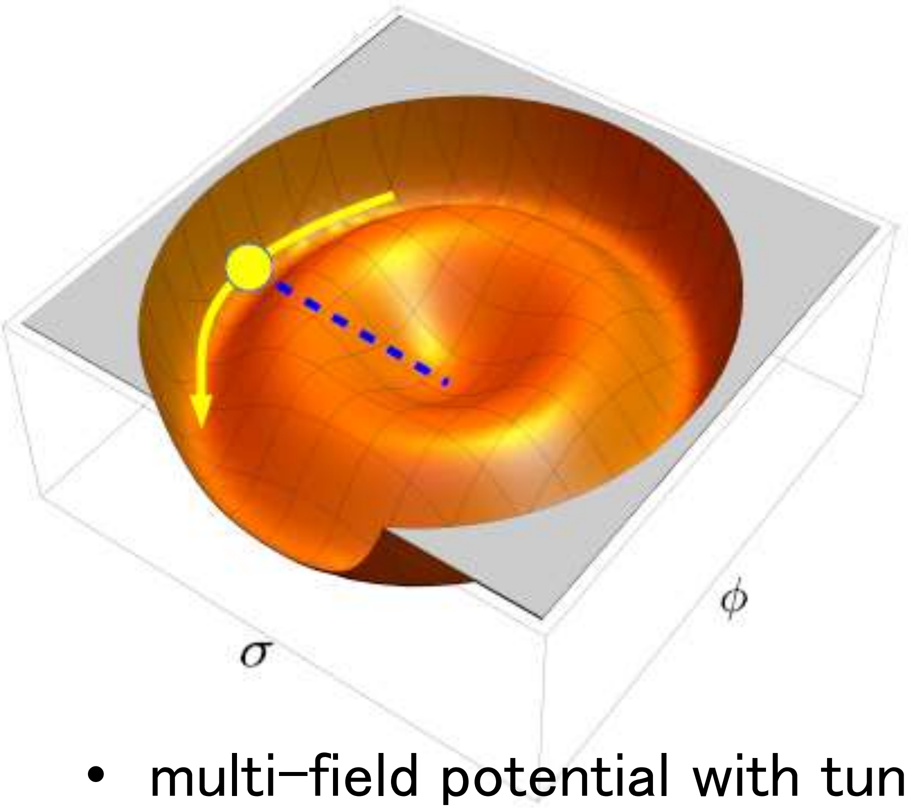
[Cai, SP, and Sasaki, arXiv:1909.13728]

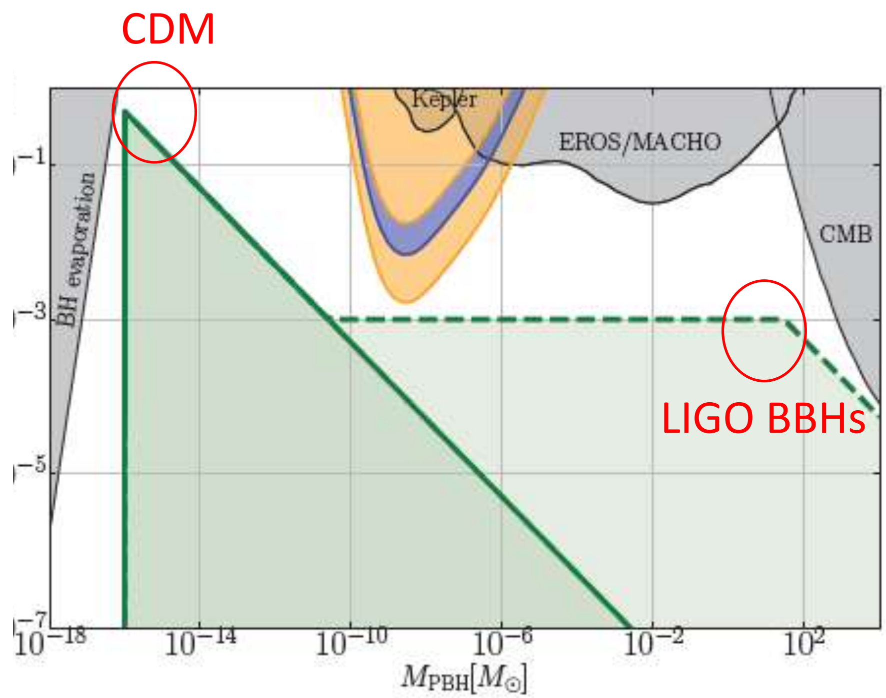


The infrared scaling of the GW spectrum is k^3, as (1) k is smaller than all the scales of the source term; and (2) k-mode reenter the horizon in the radiation dominated universe.

PBHs from multiverse

Kusenko, MS, Sugiyama, Takada, Takhistov, Vitagliano '20





- multi–field potential with tunneling barriers
- slow–roll + vacuum bubble nucleation
- bubble turns to BH when $\rho_{\rm inf} < \rho_{\rm bubble}$
- may account for both CDM and LIGO BBHs!

Future (current?) issues

length scales of the inflationary universe

⇔ targets for multi-frequency GW cosmology