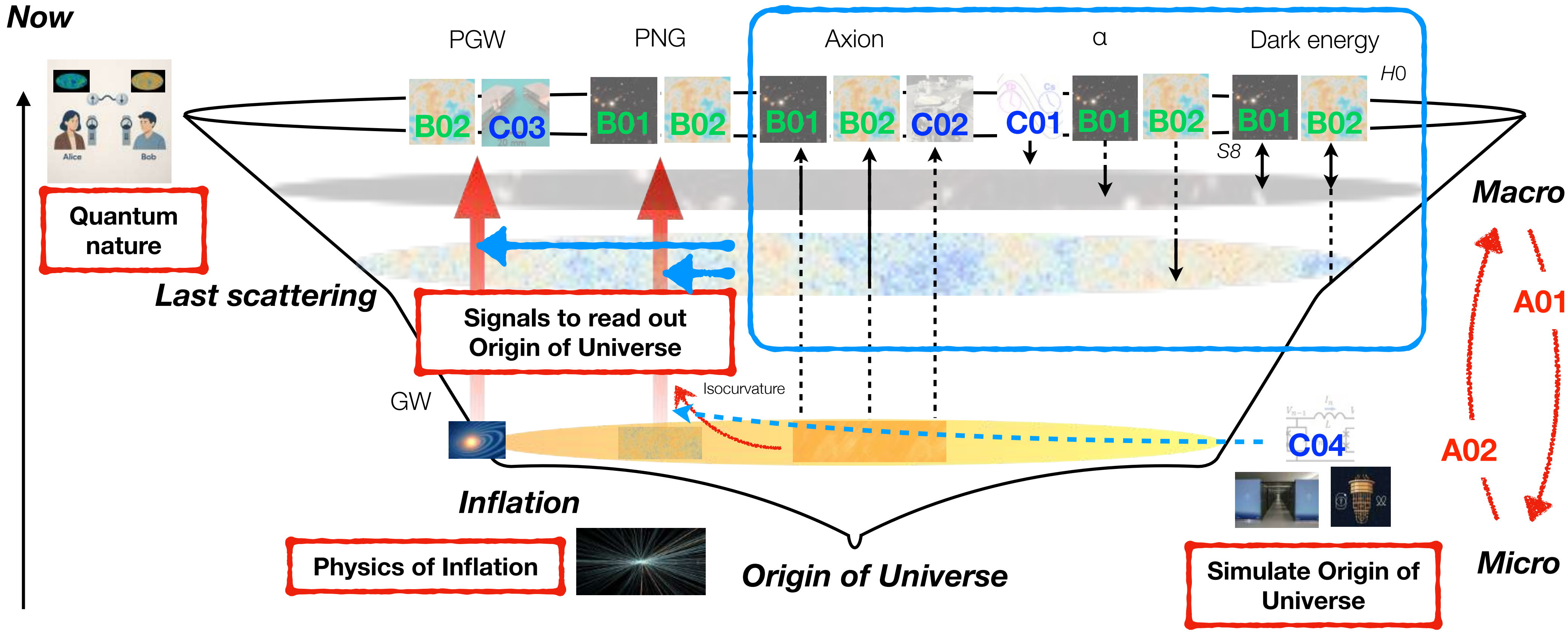
A01: 理論班（宇宙）

宇宙観測から探る宇宙創生とその量子性の理論研究

A01: Theory（Cosmology）

Theoretical Studies of the Origin of the Universe and Its Quantum Nature through Cosmological Observations

Yuko Urakawa (KEK IPNS)



Goals of A01 and members

To identify ambitious, scientifically motivated directions for probing the origin of the Universe **beyond current observational pipelines and near-term feasibility**.

$$ns(k), r, f_{\mathrm{NL}}, \ldots\ldots$$

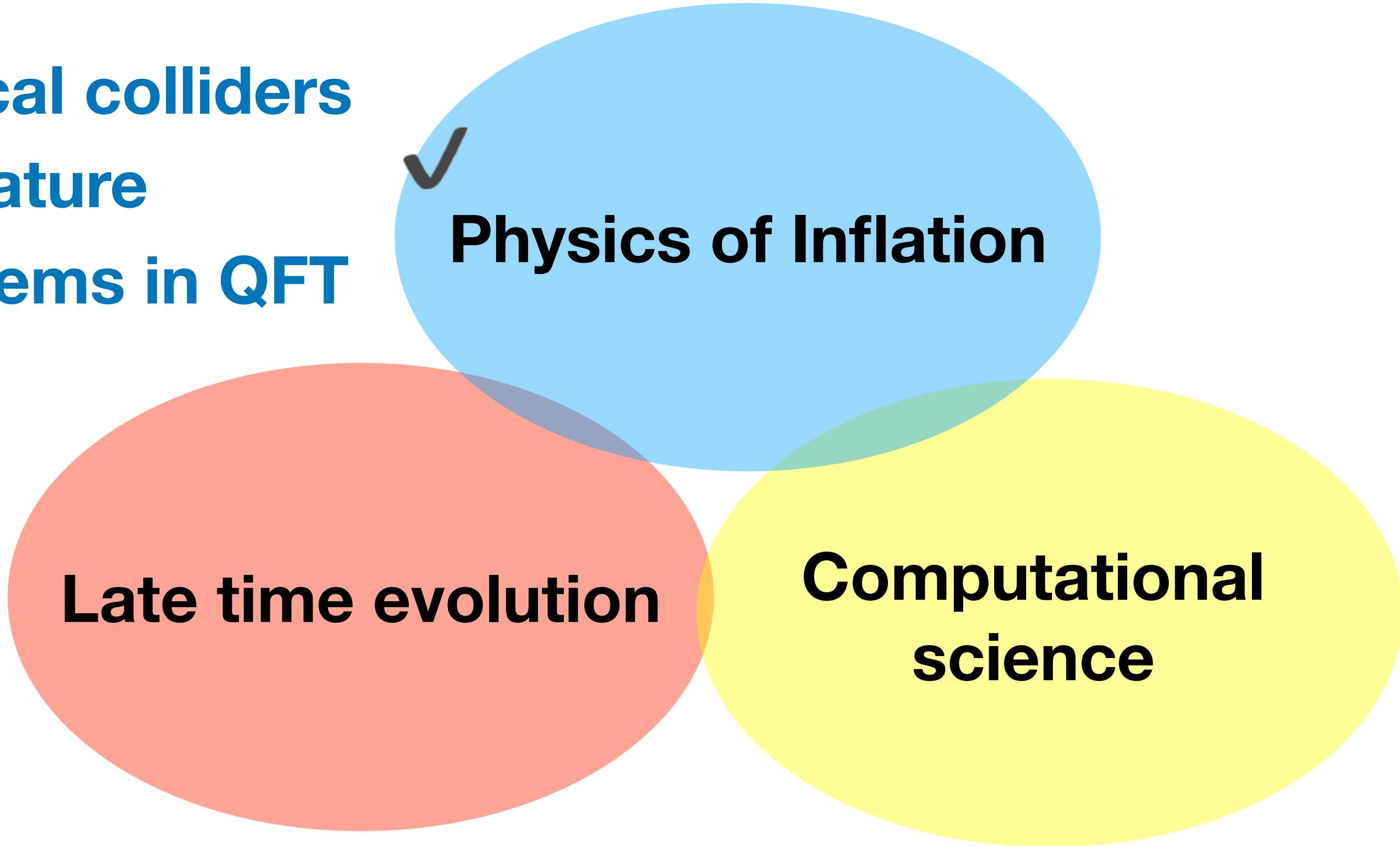
Members

PI : Yuko Urakawa (KEK, IPNS)

CoI : Tomo Takahashi (Saga), Takahiro Nishimichi (KSU), Yuichiro TADA (Fukui)

Scopes of A01

- Cosmological colliders
- Quantum nature
- Basic problems in QFT



- LSS from Non-standard IC
- Change of Phys const.
- Beyond ΛCDM (DM/DE)

- Numerical simulations
- ML/AI (incl. LLM)
- Quantum computation

Cosmological colliders

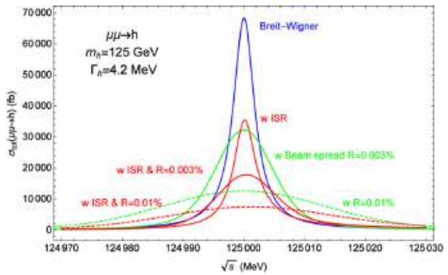
Heavy particles → **Imprints** → **Detector**

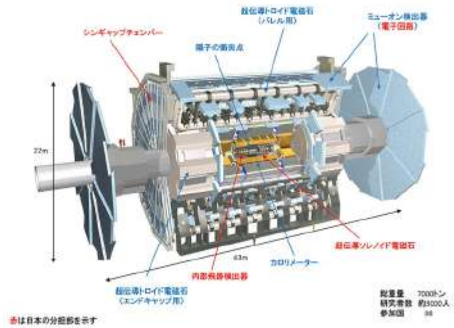
Collider experiment

Collision of particles

eg. LHC (~10^3GeV)

Resonance-like structure in collider signals

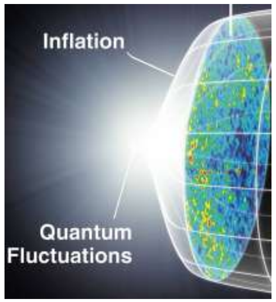




eg. ATLAS

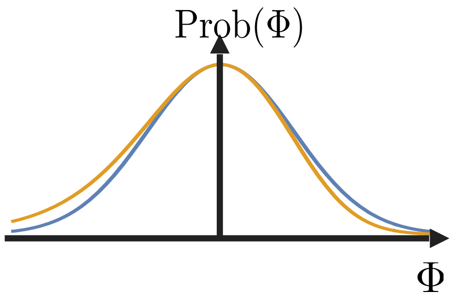
Cosmology

Heavy particles during inflation (~10^{13}GeV)

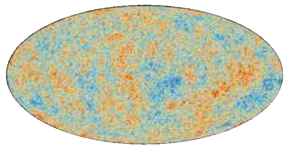


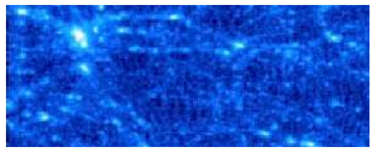
Statistical properties of primordial perturbations

Deviation fron Gaussian



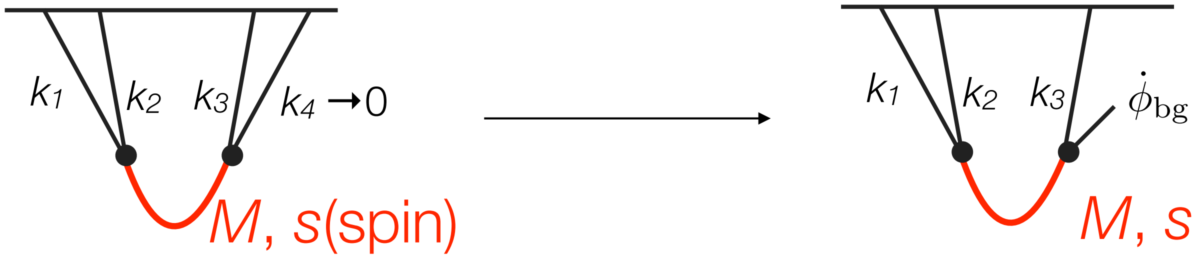
Cosmological observables





Searching for Non-Gaussianity → New probe of HEP beyond accelerator exp.

3pt fn. from spinning particle



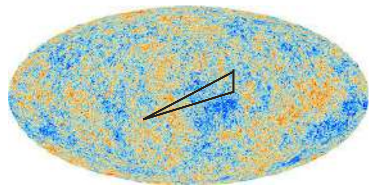
$k_3/k_1, k_3/k_2 << 1$

Particle creation

$<\delta\Phi\delta\Phi\delta\Phi> \propto P_s[\mathbf{k}_1 \cdot \mathbf{k}_3)]$

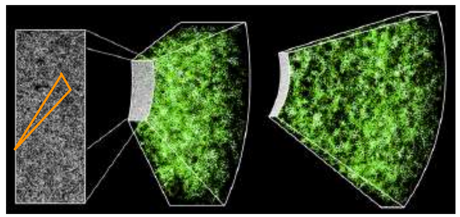
Arkani-Hamed & Maldacena (15)

1) Cosmic microwave background $<\delta T \delta T \delta T>$



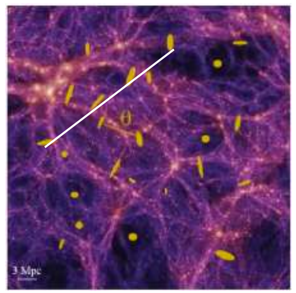
PLANCK18, Bartolo et al. (17), Franciolini et al. (18), Bordin & Cabass (19),....

2) Galaxy number count $<\delta n\ \delta n\ \delta n>$



Moradinezhad et al (18[1], 18[2]) ,...

3) Galaxy shape correlation <(shape) (shape)>

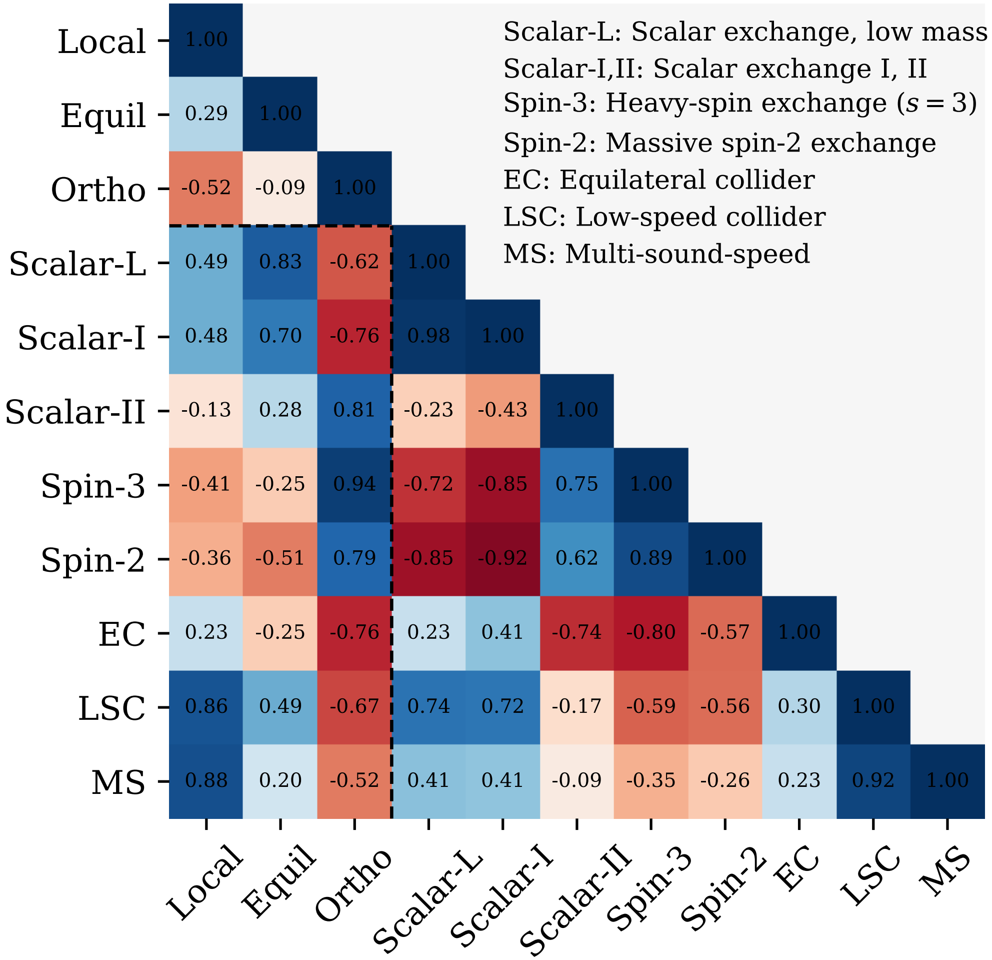


Schmidt et al (15, 16), Kogai, Matsubara, Nishizawa, Y.U. (18)
Kogai, Akitsu, Schmidt, Y.U. (20), ...

Challenge

Sohn et al. (24)

strong correlation (+1) or anti-correlation (-1)



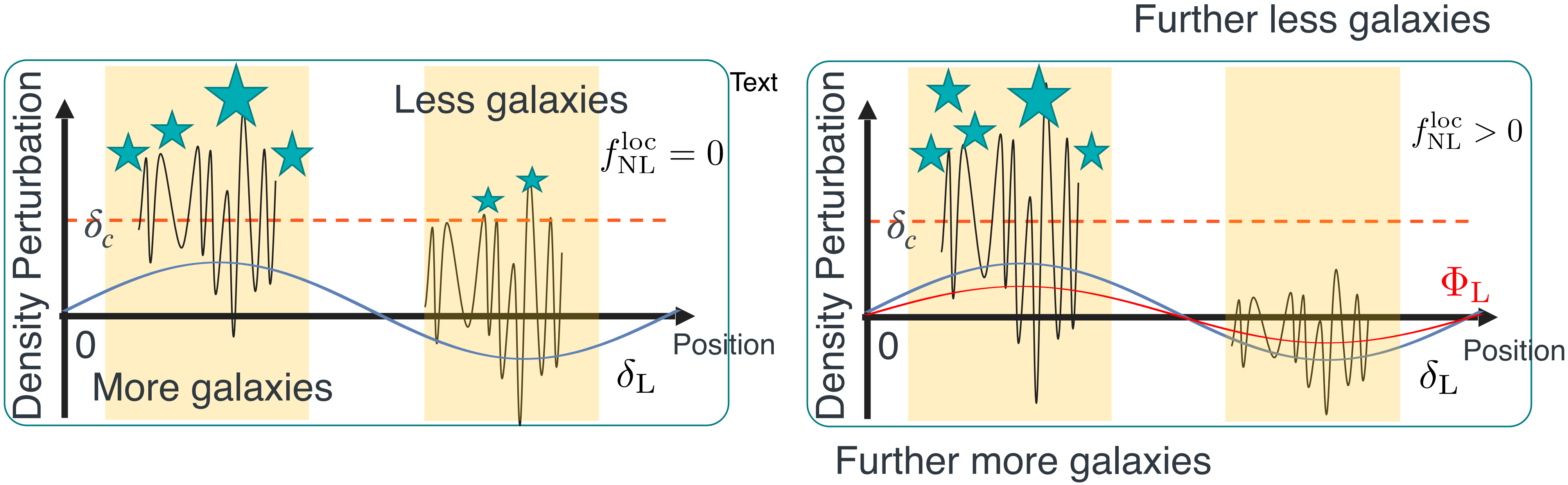
Different patters of PNG are correlated.

see also Cabass et al. (24)

Scale dependent bias

Gaussian at the onset of structure formation (Initial)

W/ (Local) PNG



$$\boxed{\delta_{\rm n}(\boldsymbol{x}) = b_\delta^{(0)}\delta_{\rm L}(\boldsymbol{x}) + b_{\rm NG}^{(0)}\left[4 f_{\rm NL}^{\rm loc}\Phi_{\rm L}(\boldsymbol{x})\right]}$$

Size of local PNG

Detailed shapes of galaxies

Mathematically, we can characterize the galaxy shapes in more detail.

Galaxy shapes (n-th moment)

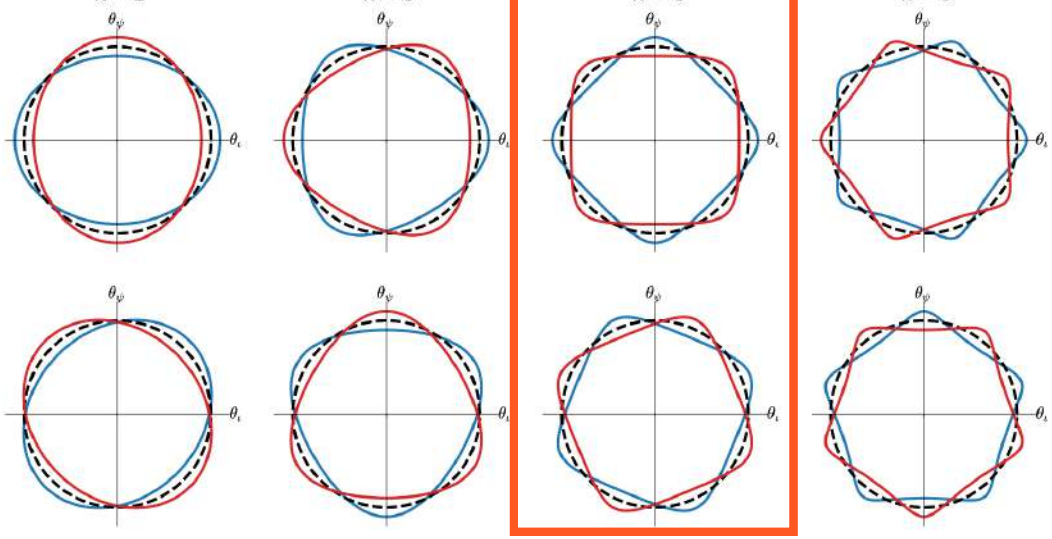
$$\gamma_{i_1 i_2 \cdots i_n}(\boldsymbol{\theta}) \propto \int d^2\theta I(\boldsymbol{\theta}) \theta_{i_1} \theta_{i_2} \cdots \theta_{i_n}$$

$$\theta_{i_n} = (x, y)$$

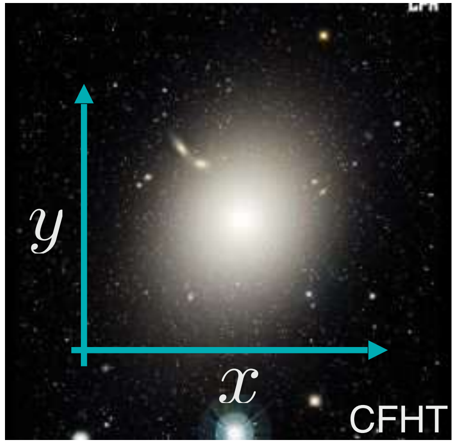
	$n = 2$	$n = 3$	$n = 4$	$n = 5$
	Quadrupole	**Octuple**	**Hexadecapole**	**32-poles**

$\gamma_+^{(n)}$

$\gamma_\times^{(n)}$



$\cdots$



Decomposition

Current observations target this.

Spin sensitive cosmological colliders

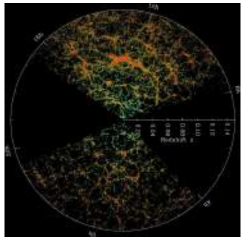
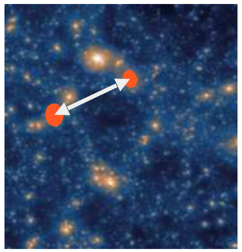
Kogai, Akitsu, Schmidt, Y.U. (21)

$$B_\Phi(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) \simeq \sum_{\ell=0,2,\cdots} A_\ell \mathcal{P}_\ell(\hat{\boldsymbol{k}}_\mathrm{S}\cdot\hat{\boldsymbol{k}}_\mathrm{L}) f_\ell(k_\mathrm{S},k_\mathrm{L}) P_\Phi(k_\mathrm{s}) P_\Phi(k_\mathrm{L})$$

spin *l* particles during inflation

exclusively in nth moment galaxy shape

(When non-linear effects are negligible)

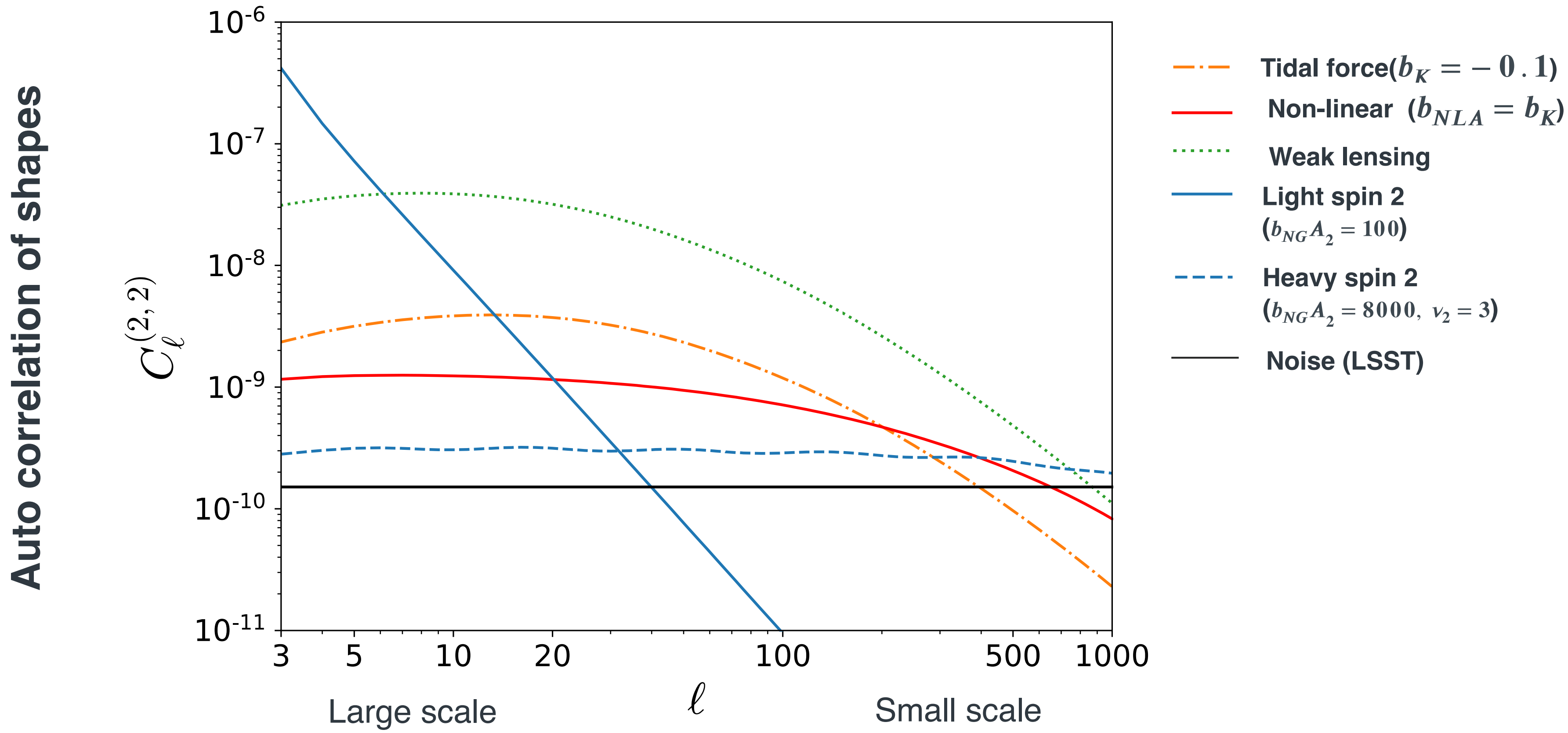
PNG	Observables	Bias
$\sim A_0\mathcal{P}_0(\hat{\boldsymbol{k}}_\mathrm{S}\cdot\hat{\boldsymbol{k}}_\mathrm{L})$ $(=4f_\mathrm{NL}^\mathrm{loc})$	Number density (Scalar) 	$\delta_\mathrm{n}(\boldsymbol{k}) = [b_\delta^{(0)} + 4b_\mathrm{NG}^{(0)} f_\mathrm{NL}^\mathrm{loc}\mathcal{M}^{-1}(k)]\delta_\mathrm{m}(\boldsymbol{k})$
$\sim A_2\mathcal{P}_2(\hat{\boldsymbol{k}}_\mathrm{S}\cdot\hat{\boldsymbol{k}}_\mathrm{L})$	Quadruple shape (2nd moment) 	$g_{ij}(\boldsymbol{k}) = [b_K^{(2)} + b_\mathrm{NG}A_2\mathcal{M}^{-1}(k)][\hat{k}_i\hat{k}_j]^\mathrm{TL}\delta(\boldsymbol{k})$
$\sim A_n\mathcal{P}_n(\hat{\boldsymbol{k}}_\mathrm{S}\cdot\hat{\boldsymbol{k}}_\mathrm{L})$	2nth pole shape (n-th moment)	$g_{i_1 i_2\cdots i_n}$

→B01

Other contaminations for spin-2?

Kogai, Akitsu, Schmidt, Y.U. (21)

At small scales, non-linear structure formation becomes important.



Finding the imprint of heavy spin-2 is not impossible but rather challenging.

We need a more detailed understanding of bias physics.

→B01

Kogai, Akitsu, Schmidt, Y.U. (21)

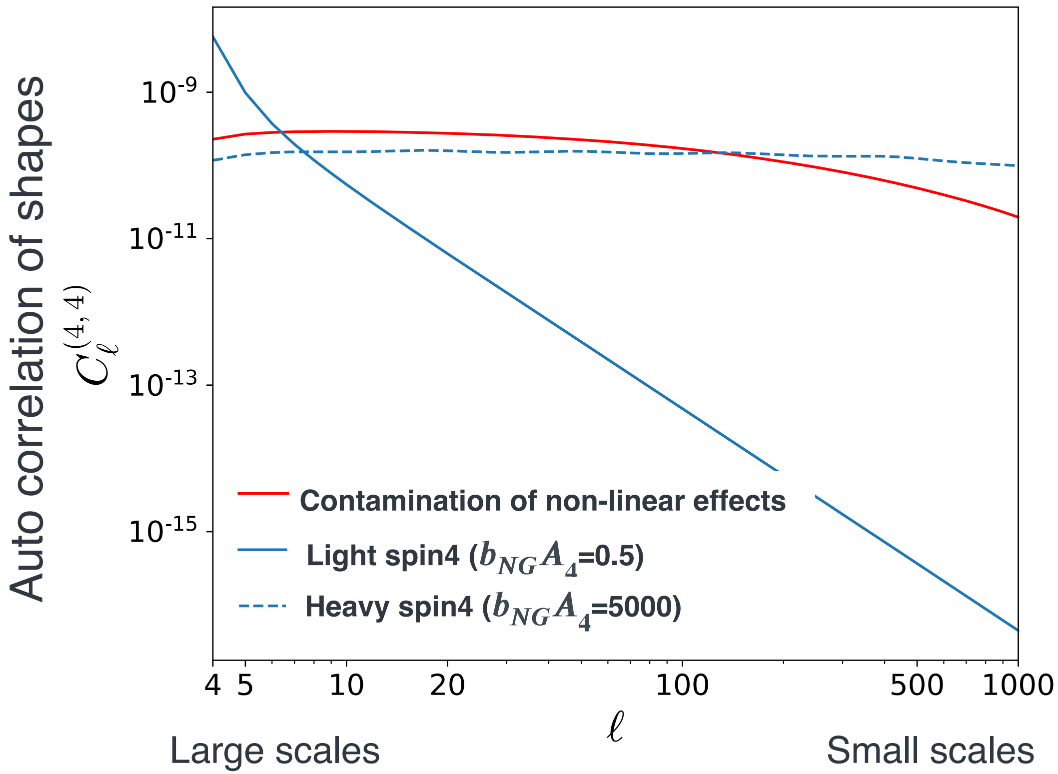
Spin-4 particle search from 2^4-pole galaxy shapes

Existence of higher spin particles → Prediction of string theory

3D shape fn.

w/light spin 4	$g_{ijkl}(\boldsymbol{k}) \sim b_{\rm NG} A_4 \mathcal{M}^{-1}(k)[\hat{k}_i\hat{k}_j\hat{k}_k\hat{k}_l]\delta_{\rm m}(\boldsymbol{k})$
w/heavy spin 4	$g_{ijkl}(\boldsymbol{k}) \sim b_{\rm NG} A_4 \mathcal{M}^{-1}(k) \underline{\left(\frac{k}{k_*}\right)^{3/2} \cos\left(\nu_4 \ln\left(\frac{k}{k_*}\right) + \Theta_4\right)} [\hat{k}_i\hat{k}_j\hat{k}_k\hat{k}_l]\delta_{\rm m}(\boldsymbol{k})$

2D projected shape $\gamma_{ij}^{\rm IA}$ → **Statistics along line of sight**



- No-linear bias effect
  → Good to search for higher spin particles
- Imprints of light particles at large scales
- Imprints of heavy particles at small scales
  (Competition w/non-linear effects)

Higuchi bound $M^2 > 12\,H^2$ (for spin 4)

We need a more detailed understanding of bias physics.

Quantum nature of primordial perturbations

- Cosmological structure is widely believed to have been generated during inflation from quantum fluctuation of the inflaton.

- In most models of early Universe, the quantum coherence was lost right after the horizon crossing during inflation.

$$[\zeta(x), \pi_\zeta(y)] = i\hbar\delta(x-y)$$

Polarski and Starobinsky (1995)

↑ ~ decaying mode, difficult to detect its imprints

Off diagonal of reduced density matrix typically falls off exponentially

Kiefer, Lohmer, Polarski, Starobinsky (1996),....

Possible way-out (even if contriving)?

Bell test

<u>CHSH inequality</u>

Alice eg. S_x, S_z Bob

Measurements A, A' Measurements B, B'

± 1 ± 1 ± 1 ± 1

Bell operator $$\mathcal{B} = AB + AB' + A'B - A'B'$$

1) Locality: no influence faster than light

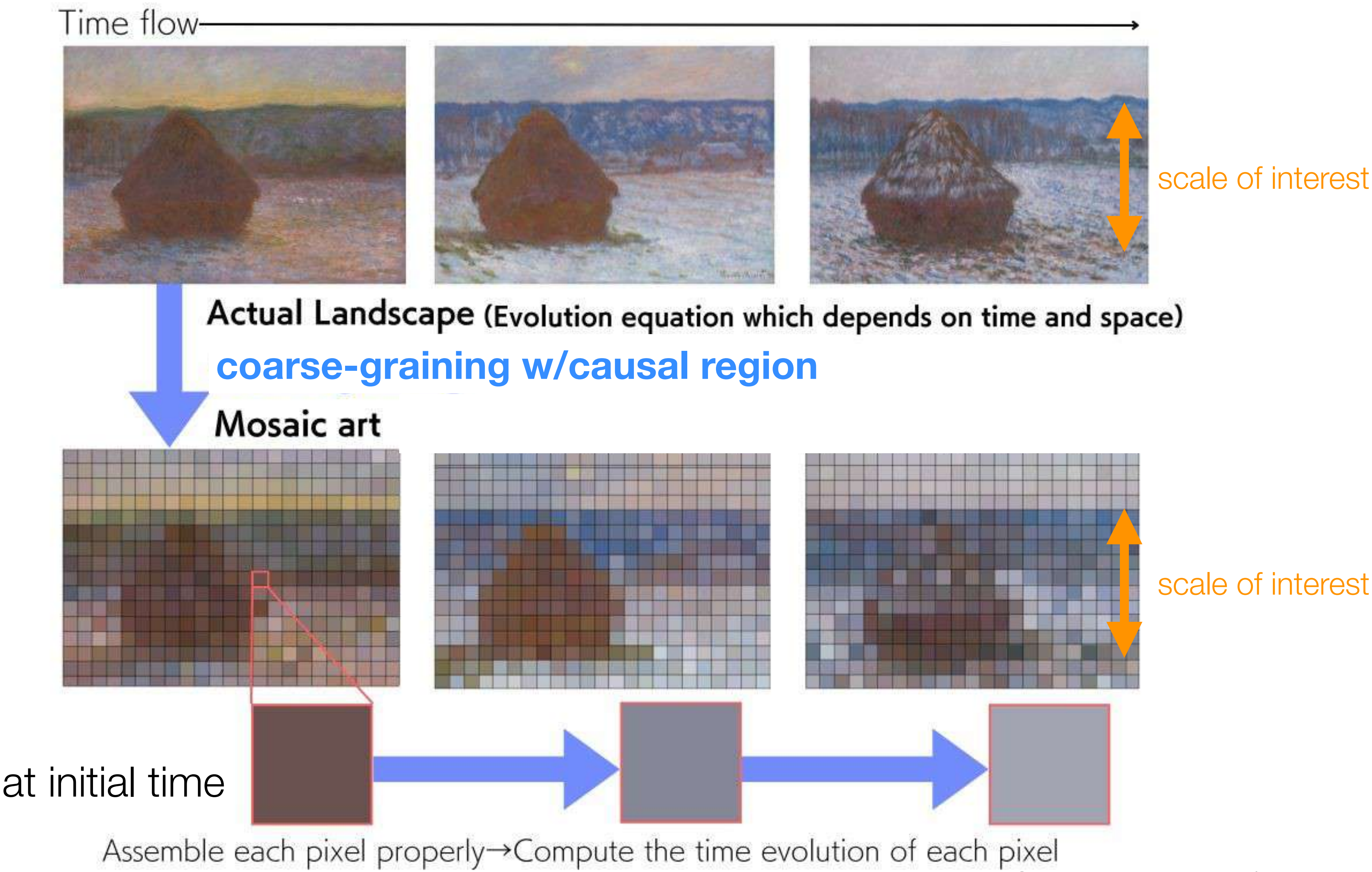
2) Freedom of choice: settings independent of hidden variables $\longrightarrow$ $\left|\mathrm{Tr}\left[\rho\mathcal{B}\right]\right| \leq 2$

3) Realism: outcomes exist before measurement

If $\left|\mathrm{Tr}\left[\rho\mathcal{B}\right]\right|$ >2, while 1) &2) hold, 3) does not hold Quantum nature

Separate Universe approach ~ Mosaic art

Salopek&Bond(90)



Condition for separate universe [Classical]

Tanaka & Y.U. (JCAP 2021, PRL 2024)

【Locality】

The Lagrangian density **(before solving gauge constraints)** is determined by a local function of coarse-grained field $\{\varphi^a\}$, i.e.,

$$\mathcal{L}(x) = \mathcal{L}\left[\{\varphi^a(x)\}\right]$$

【sDiff】

The action remains invariant under the spatial Diff.

$$x^i \to \tilde{x}^i(t, \mathbf{x})$$

➡ Validity of separate universe (☆)

including… 1) All the large scale fluctuations, incl. GWs.

2) Contributions of all integer spin fields

From classical to quantum

Effective action after coarse-graining the hard modes (~ subhorizon modes)

Quantum fields

How to formulate these conditions of SU for quantized system?

What is locality in q-system?

How to deal with gauge constraints (especially MC) in q-system?

These aspects are closely related to

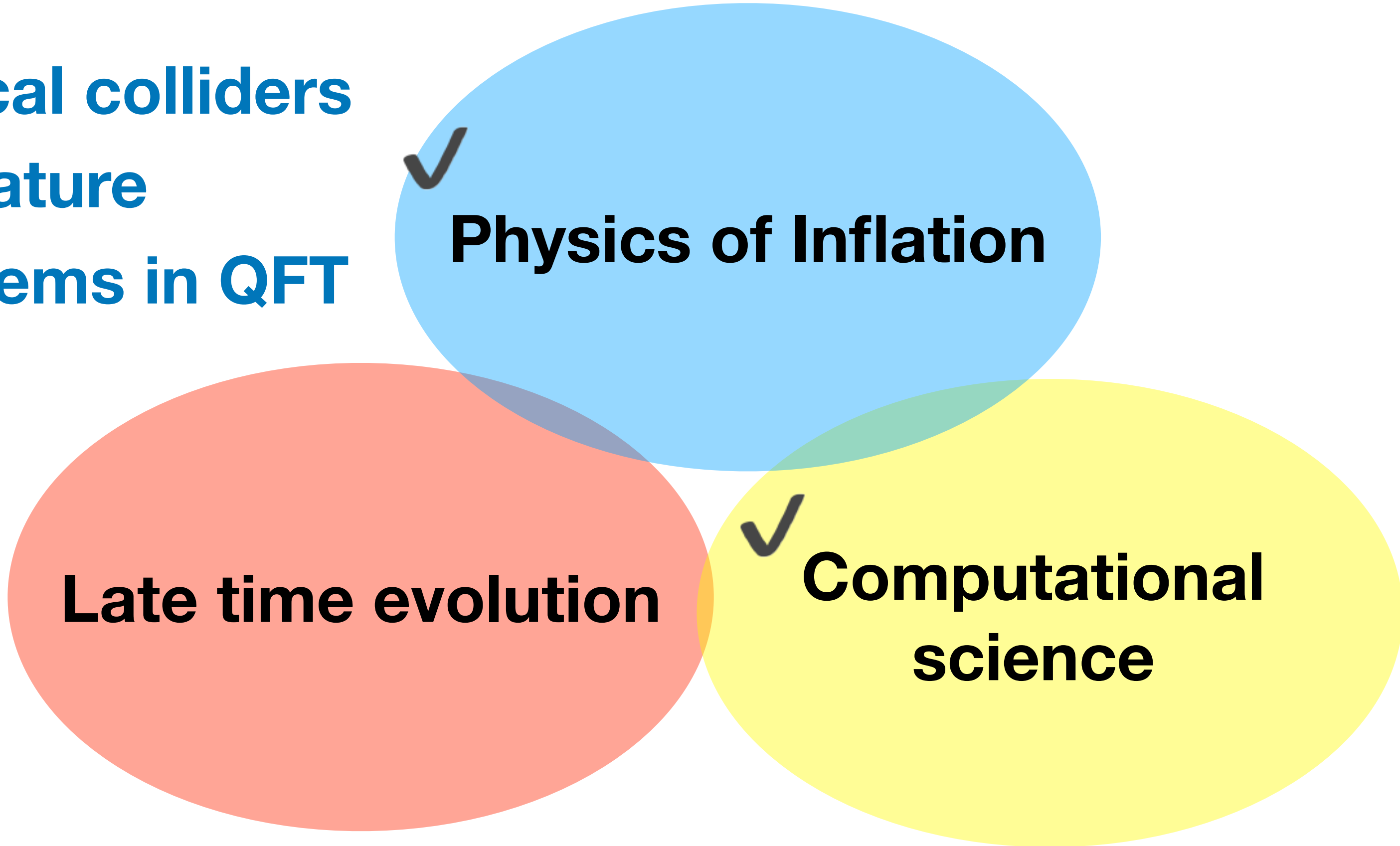
- IR physics in QED, scattering of gravitons Kuramoto, Tanaka & Y.U. (in prep)
  (IR triangles, Faddeev-Kulish, etc…) Strominger + (13,….)

…. potentially

- Edge modes and potentially Entanglement entropy/SSB etc… Donelly & Freidal (17)
- Spontaneous symmetry breaking (in cosmology) **→C04 (?)**

Scopes of A01

- Cosmological colliders
- Quantum nature
- Basic problems in QFT



- LSS from Non-standard IC
- Change of Phys const.
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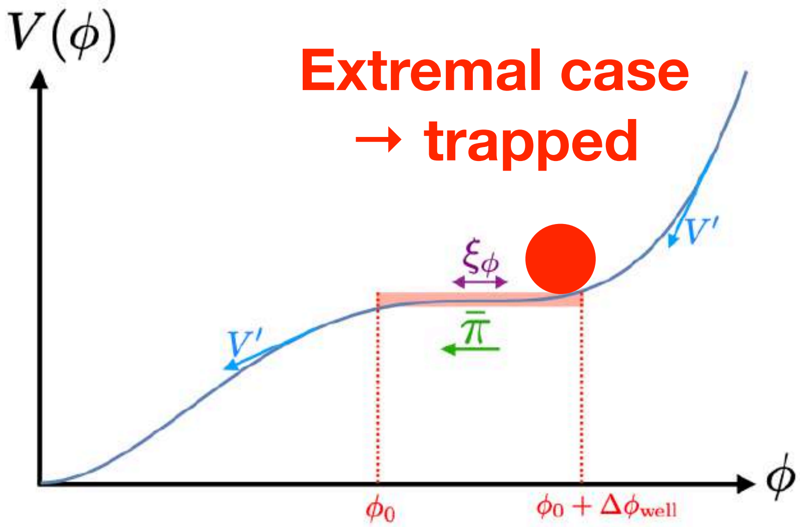
Beyond gradient expansion



Pattison et al. (2017, 2021), Ezquiaga et al. (2020).
Figueroa et al. (2020),....

Figure from Pattison et al. (2017)

- Significant diffusion effect
- Interesting ballpark for PBH formation
- Deviation from Gaussian (Heavy tail)?

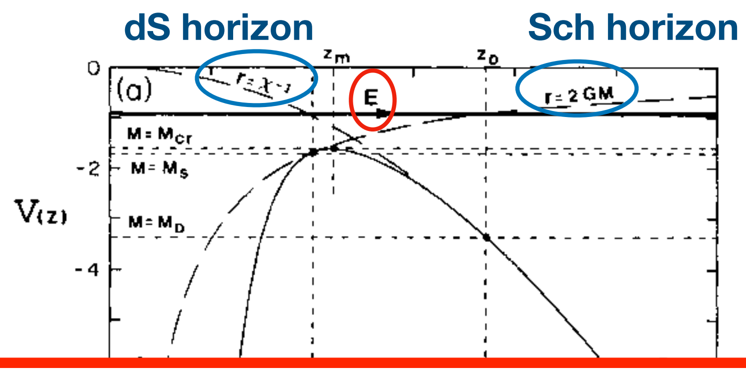
Two brunches of PBH formation {
Adiabatic brunch
Bubble brunch (Baby universe)

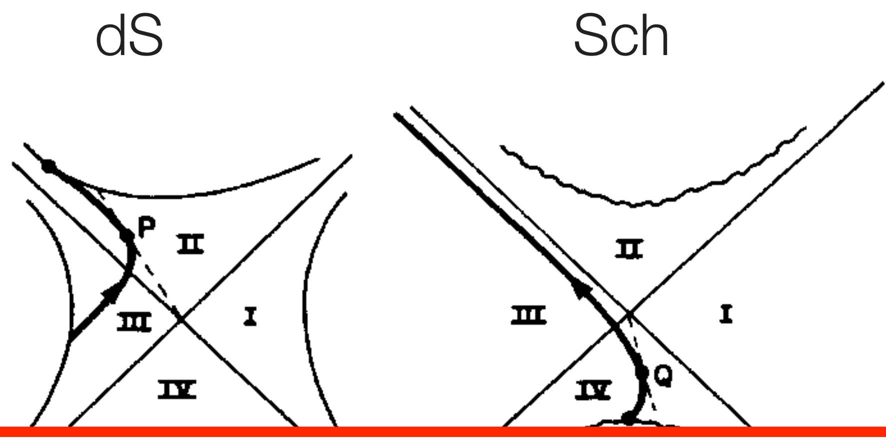
Blau, Guendelman, and Guth (1987)
Garriga, Vilenkin, and Zhang (2016)

Recall Nomura-san's talk

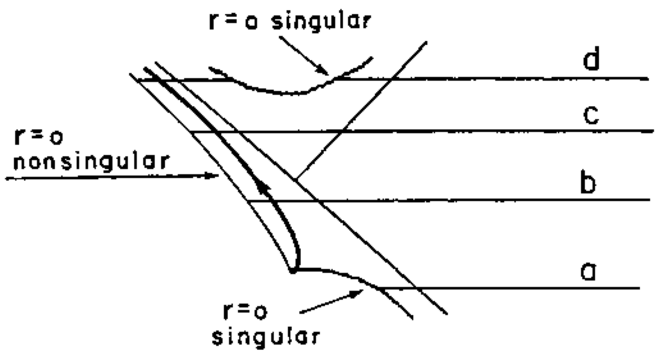
Baby Universe

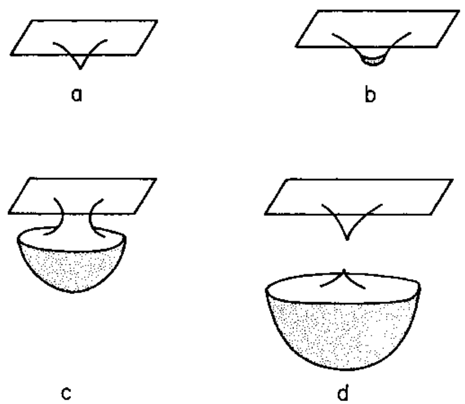
Blau, Guendelman, and Guth (1987)





In summary
Interior of bubble eternally inflates, while it's seen as BH from outside

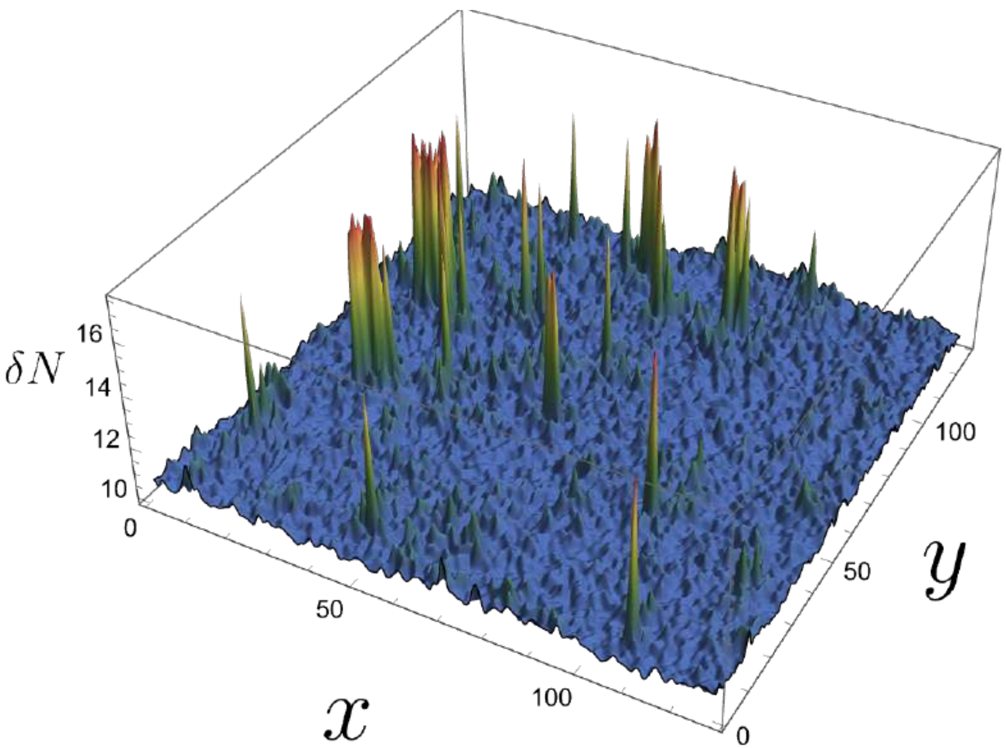


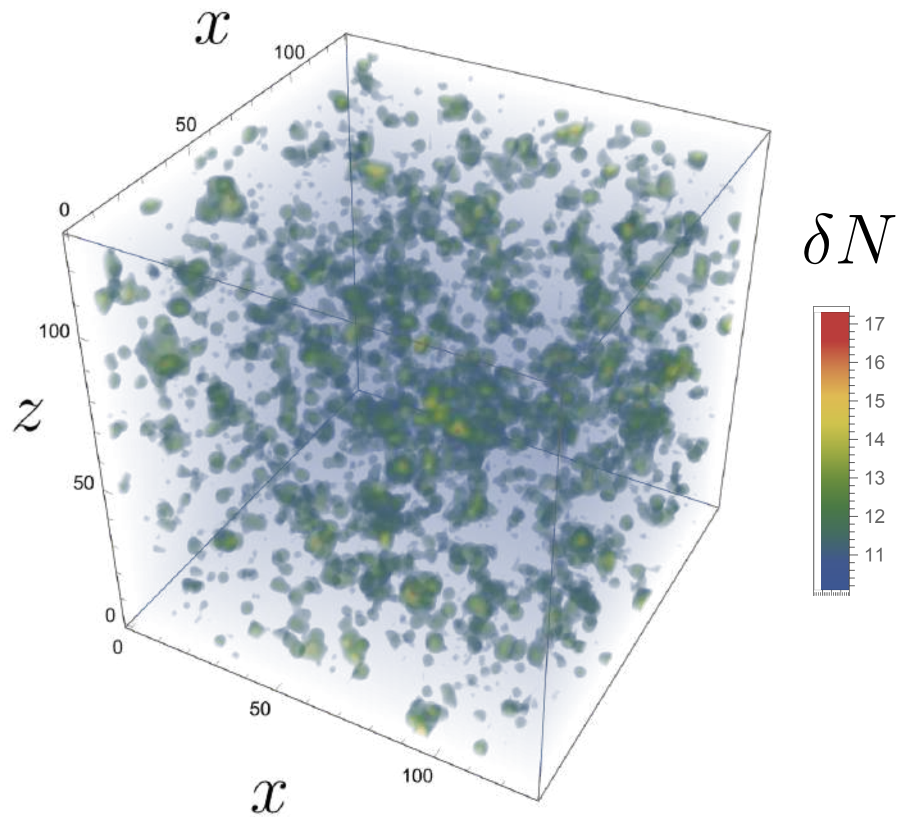


Development of Numerical schemes

Saha, Tada, Y.U (2026)
W/Saha.... (in prep)

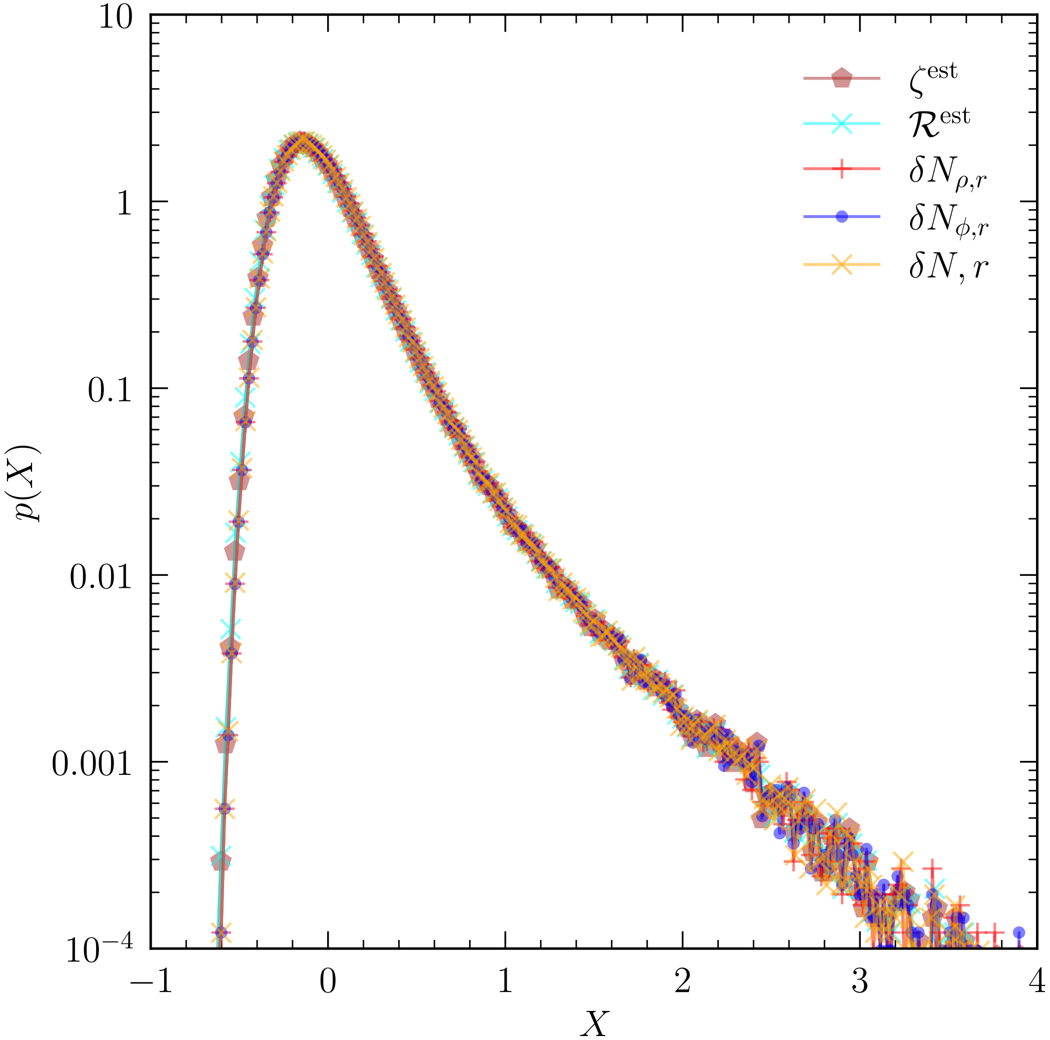
Trapping happens as a rare process → Baby Universe (?)





Please go to the poster by Saha

Heavy non-Gaussian tail



$P_{\zeta,\ \max} > 10^{-2}$

Two brunches of PBHs?

Please go to the poster by Saha

Scopes of A01

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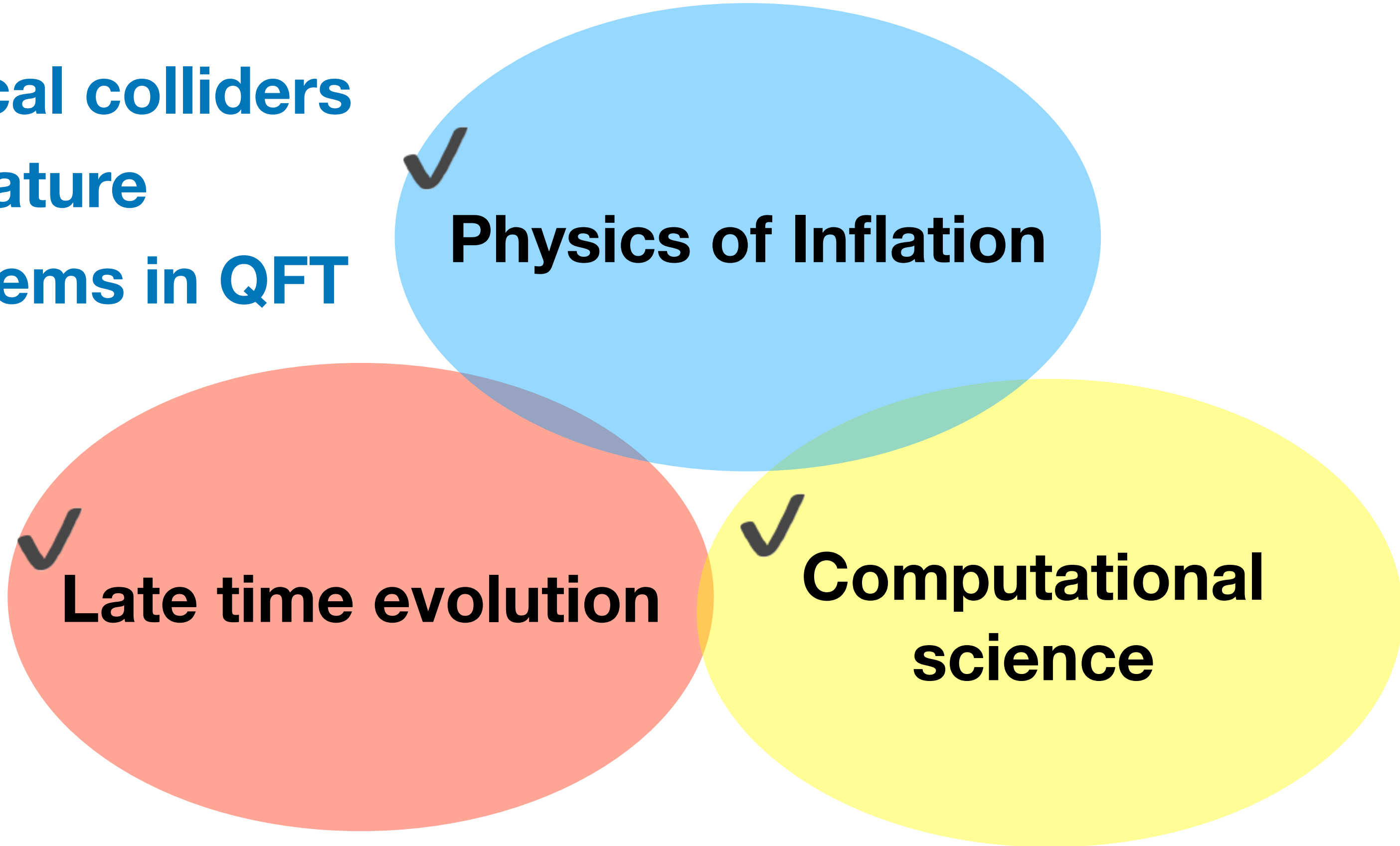

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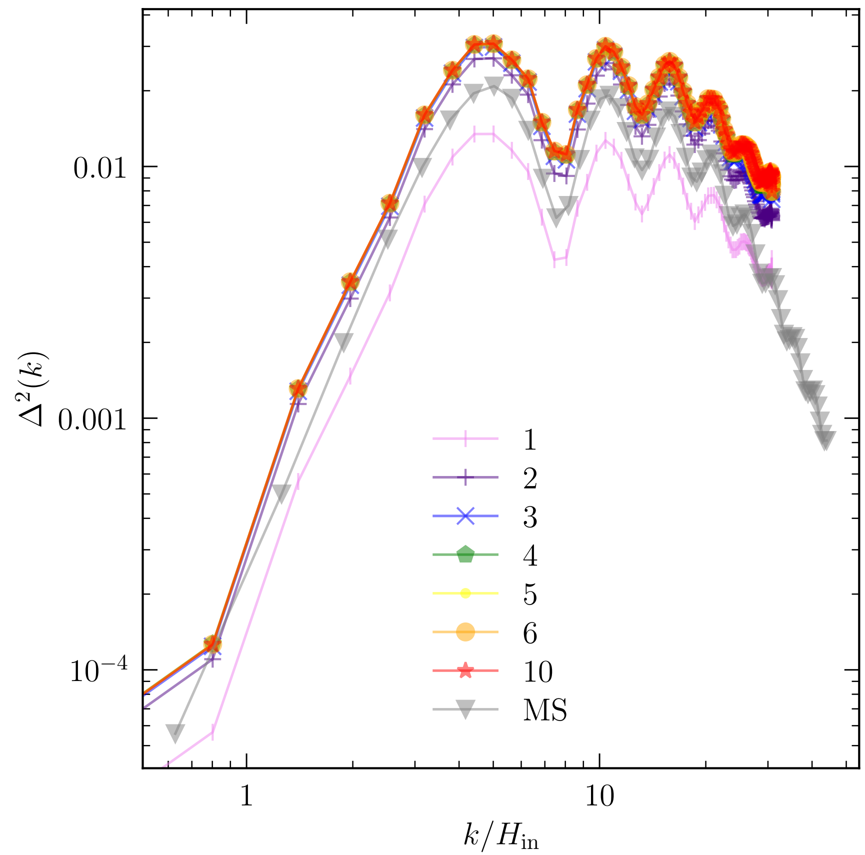
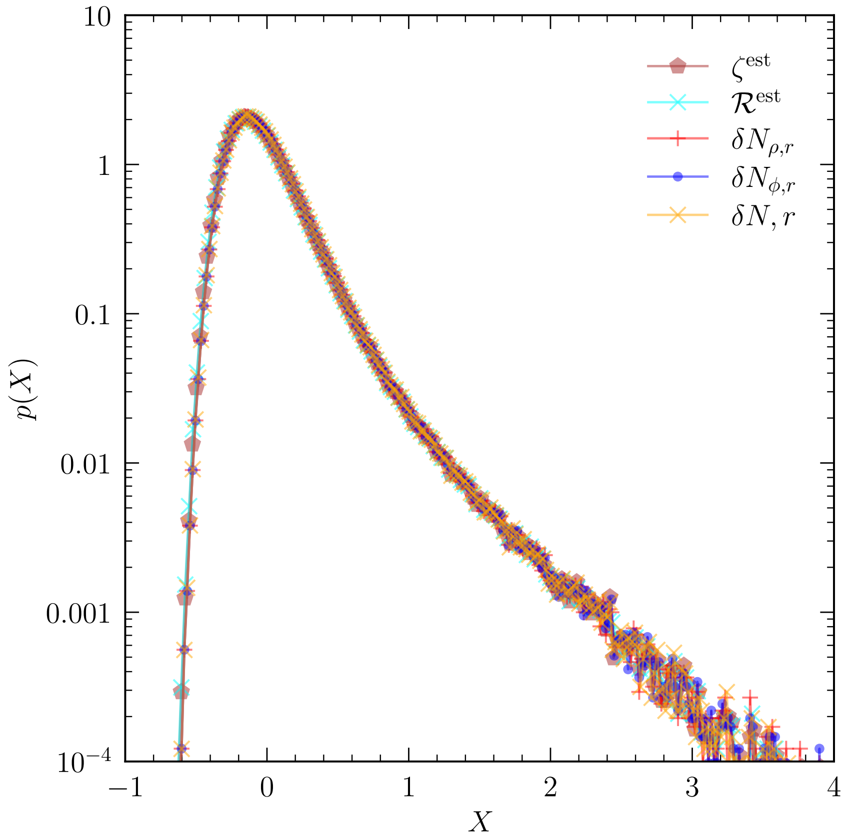
Prediction from flat potential

W/Saha… (in preparation)

Small scale enhancement of P_ζ



Heavy non-Gaussian tail



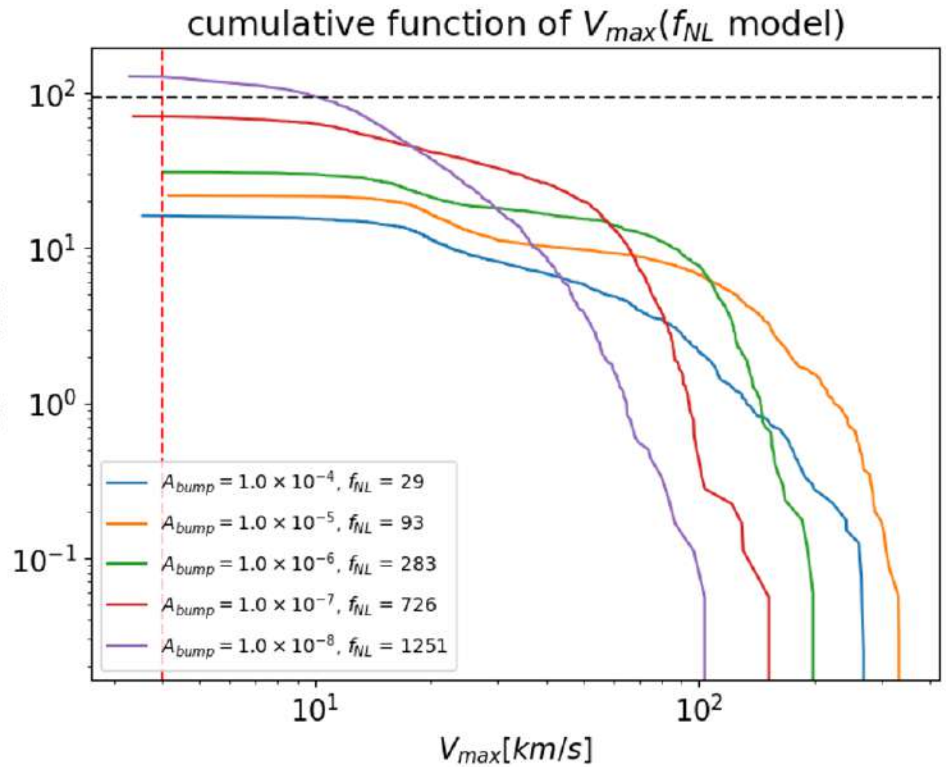
→ B01

Impact on substructure (N-body)

Sakuma & Nishimichi (in prep)

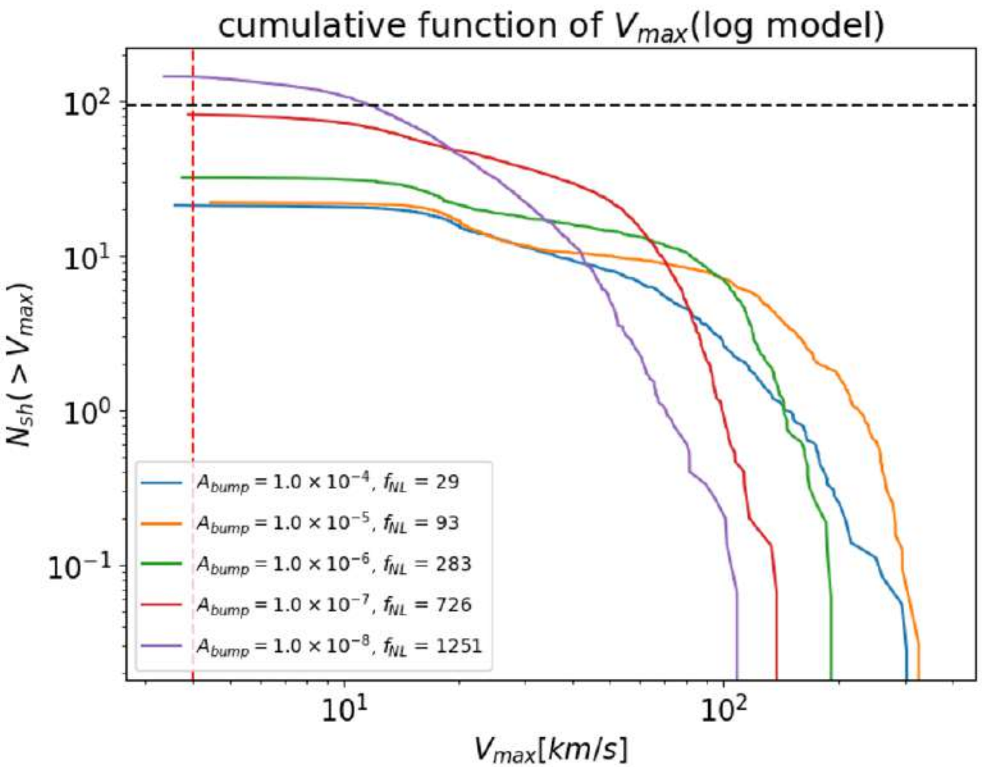
Small scale enhancement of P_ζ

of satellite galaxies



Heavy non-Gaussian tail

$$\zeta = -\frac{1}{\beta}\ln(1-\beta\zeta_g)$$ Atal + (2019)

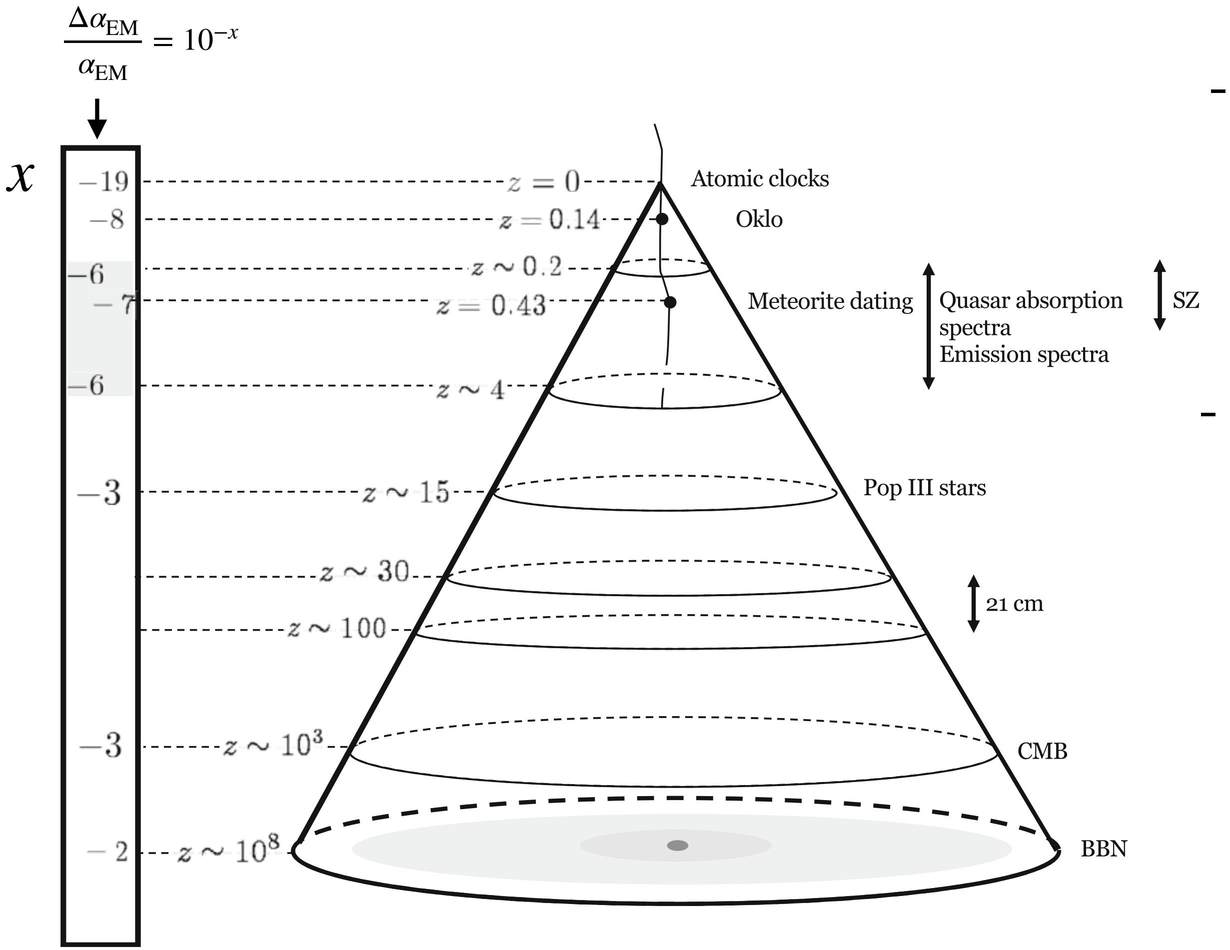


See also Coulton, Philcox, Villaescus-Navarro (24)

Prepare more general and accurate IC for N-body from lattice

→ **B01, B02**
→ **C01, C02**

Constraints on fundamental constants



[Uzan 2410.07281]

- Light dilaton phenomenology

- If $m_i(\phi) = A(\phi) m_i^{(0)} \qquad (i = e, p, \cdots)$

e.g., C.Burgess (2025)

fifth force problem needs to be addressed together

relaxes Hubble tension?

Sekiguchi & Takahashi (2020)

Constraints become more stringent as we approach the present epoch.

+ More to come during 5 years!

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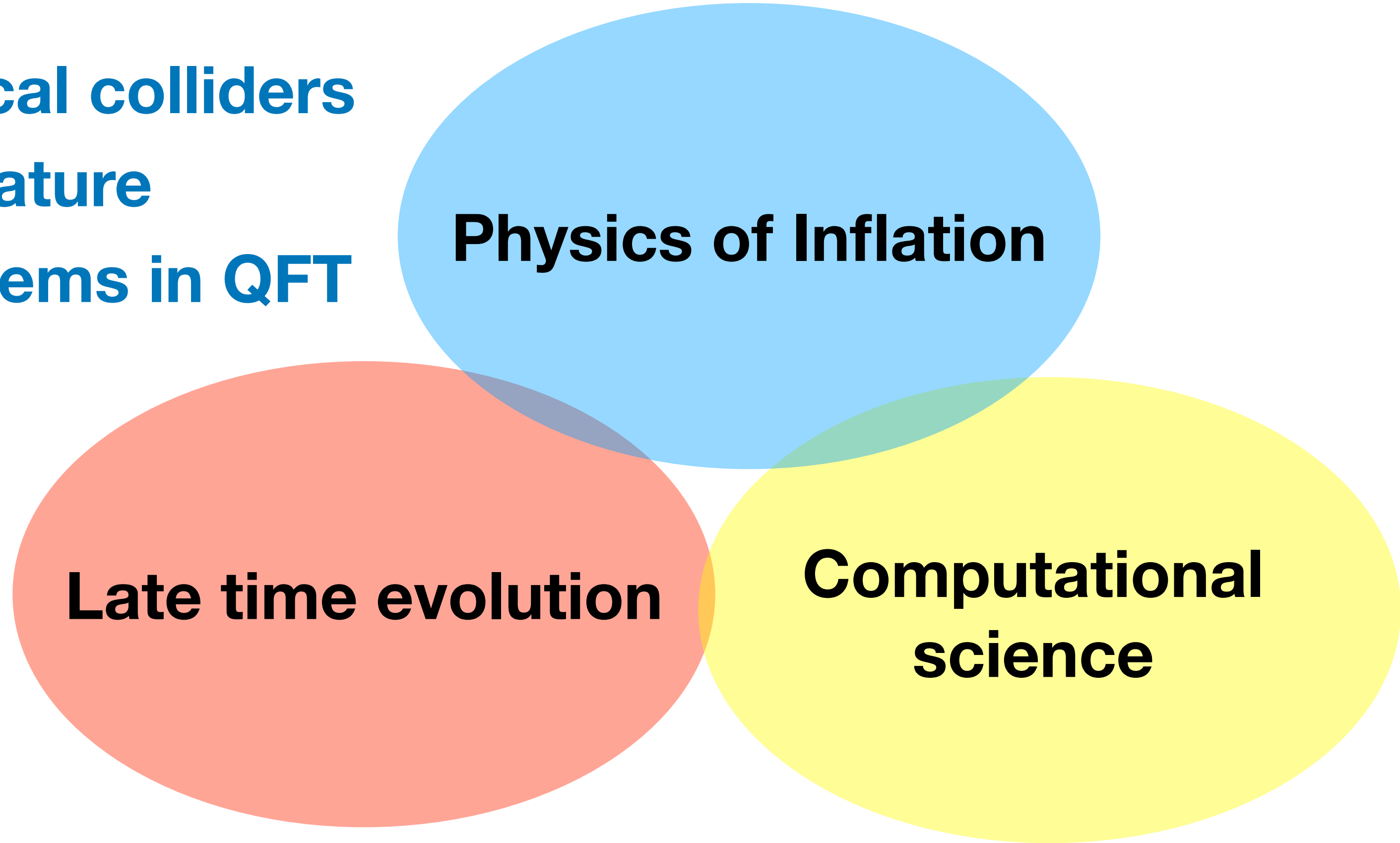

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