Inhomogeneous dark energy formulation in light of hints of cosmological principle breakdown

Yue Nan

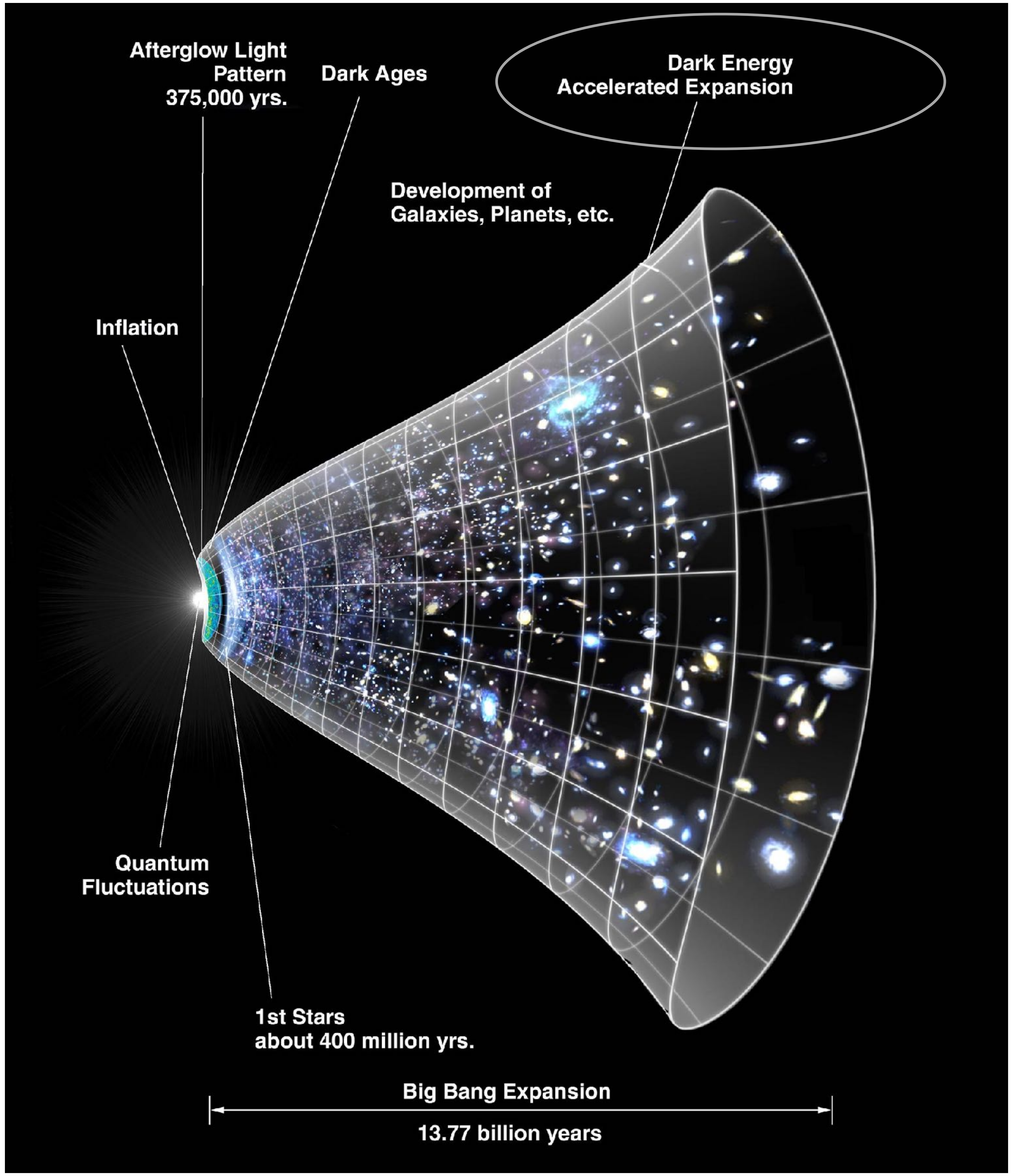
Based on
[Y. Nan and Kazuhiro Yamamoto, 2022]
[Koki Yamashita, YN, Yuuki Sugiyama, and Kazuhiro Yamamoto, 2022]
[YN, Kazuhiro Yamamoto, Hajime Aoki, Satoshi Iso, and Daisuke Yamauchi, 2019]

10/27/2022 @ Kavli IPMU PostDoc Colloquium

Outline

1. Motivation
2. Formulation of Dark Energy with spatial inhomogeneities
3. Formulation on modification to Observables and LSS power spectrum
4. Summary

1. Introduction. ΛCDM model and Dark Energy



Credit: NASA/WMAP Science Team/ Art by Dana Berry

- ΛCDM prediction for CMB fluctuations and structure formation: successful description
  - Cosmological principle: homogeneity and isotropy
  - Perturbations to isotropic background in FLRW metric

$$\Omega_\Lambda \simeq 0.7 \quad \Omega_m \simeq 0.3 \quad \Omega_K \simeq 0$$

- Negative pressure
  —> Simplest realization:
  Cosmological Constant (CC) Λ

Dark energy beyond Λ: Theories and observations

- The Cosmological Constant Problem CCP)
  - Fine-tuning ↔ vacuum energy of QFT? : $\mathcal{O}(10^{122})$ discrepancy in energy scale
  - Coincidence ↔ why late-time, anthropic epoch?
- Nature of DE? (Vacuum energy? Physical particle/field? Modification to gravity?)
- Λ inconsistent for dS (Swampland conjecture $|\nabla V| \geqslant cV$) → dynamical models favored

[Obied+2018][Garg&Krishnan 2018][Ooguri+2019]…

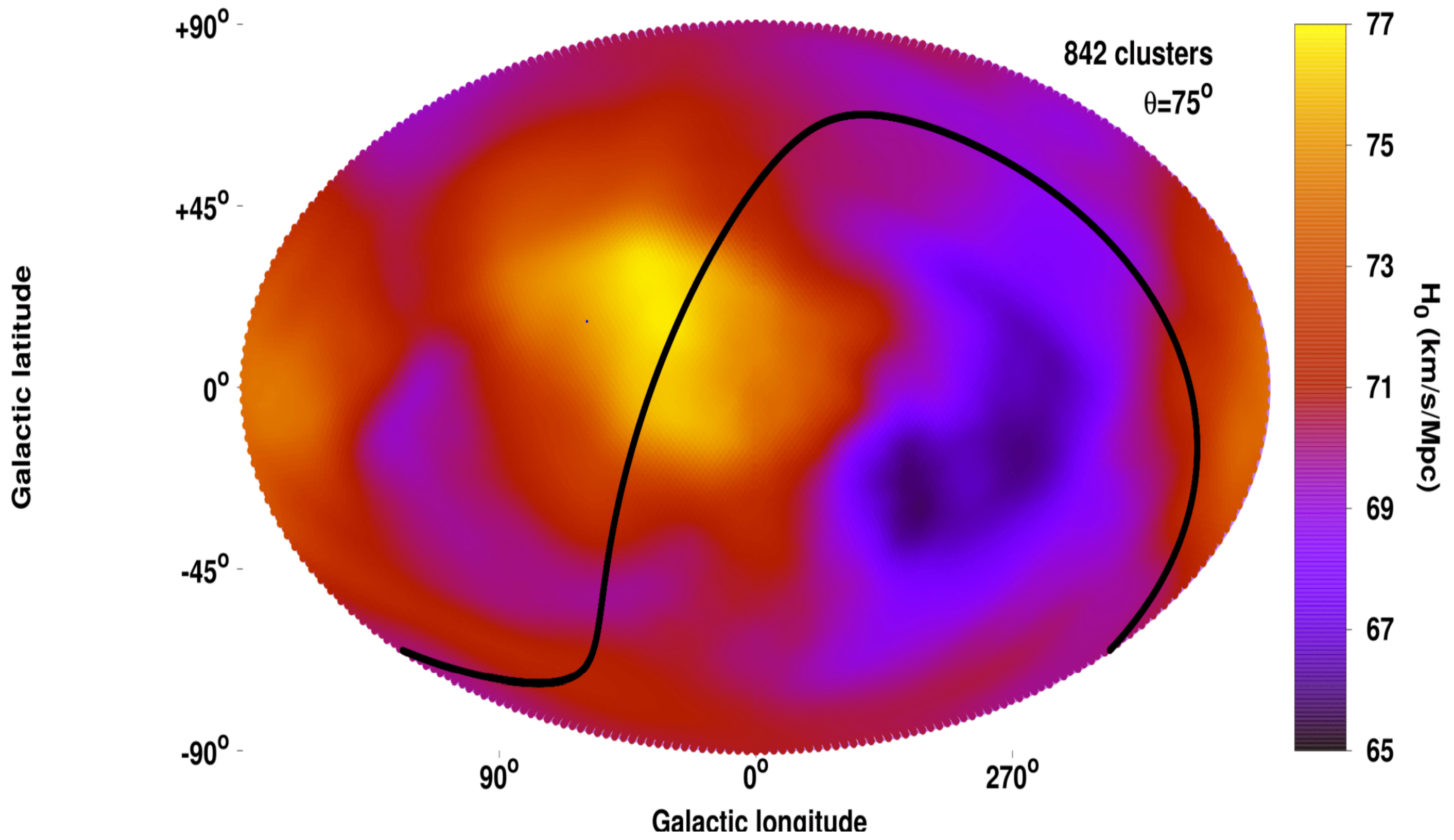
Tensions and anomalies in Observations/Analyses

- H_0 , S_8 (σ_8) (?) tension between late-time/local LSS v.s. early-time CMB (↔Physical scale of BAO)
- Anomalies (CMB dipole/low multiples, huge structures in LSS (↔ homogeneity scale of the Universe?) fine-structure const. … [Webb 2012]) **(Rev. [L. Perivolaropoulos 2014])**
- **And also the cosmic dipoles and anisotropy in expansion rate**?

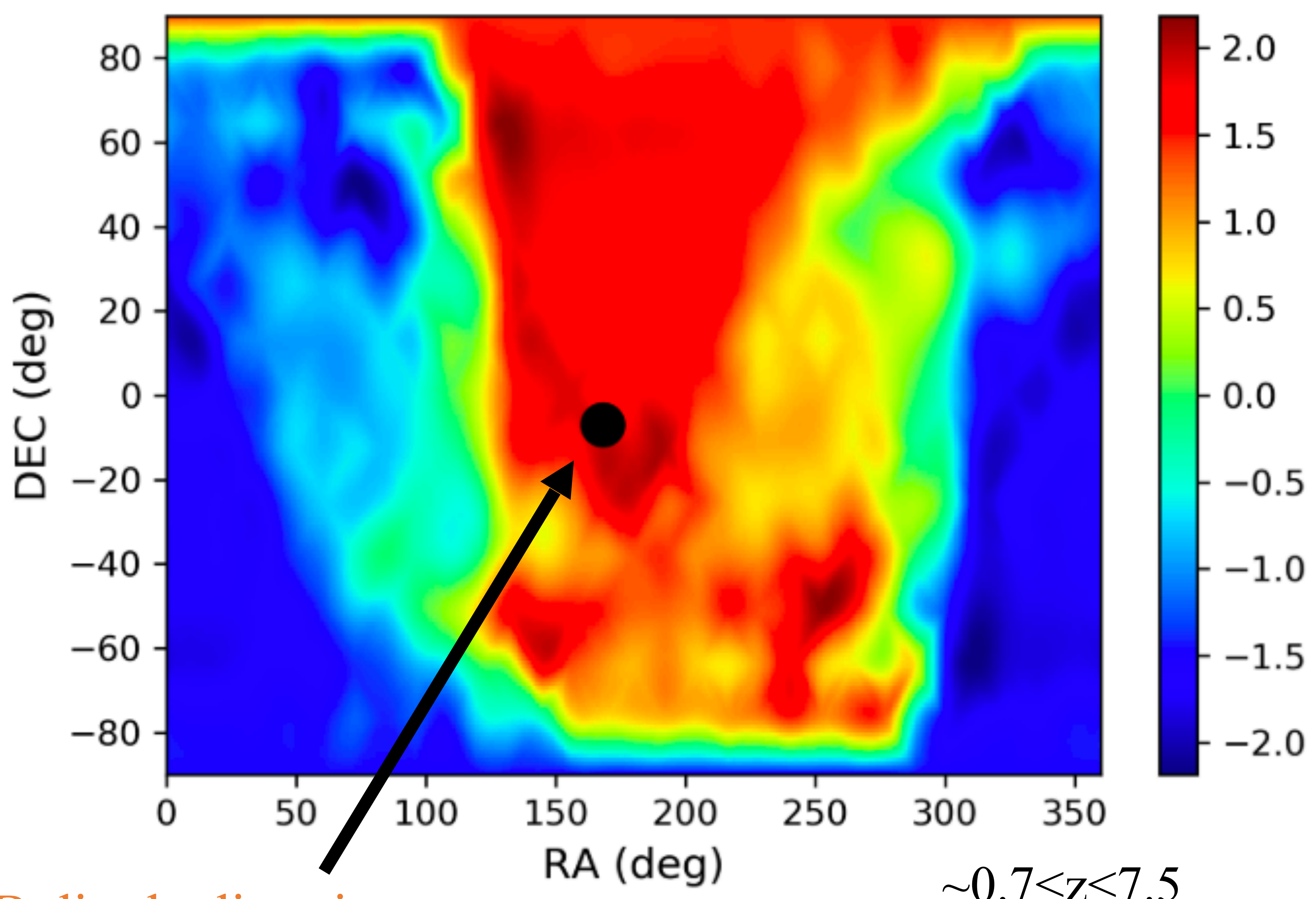
Beyond cosmological principle: breakdown signals?

- Paradigm: ΛCDM in cosmological principle: isotropy and homogeneity **(e.g., Λ), but…**

[K. Migkas+ 2020,2021]



[O. Luongo+2021]



~0.7<z<7.5

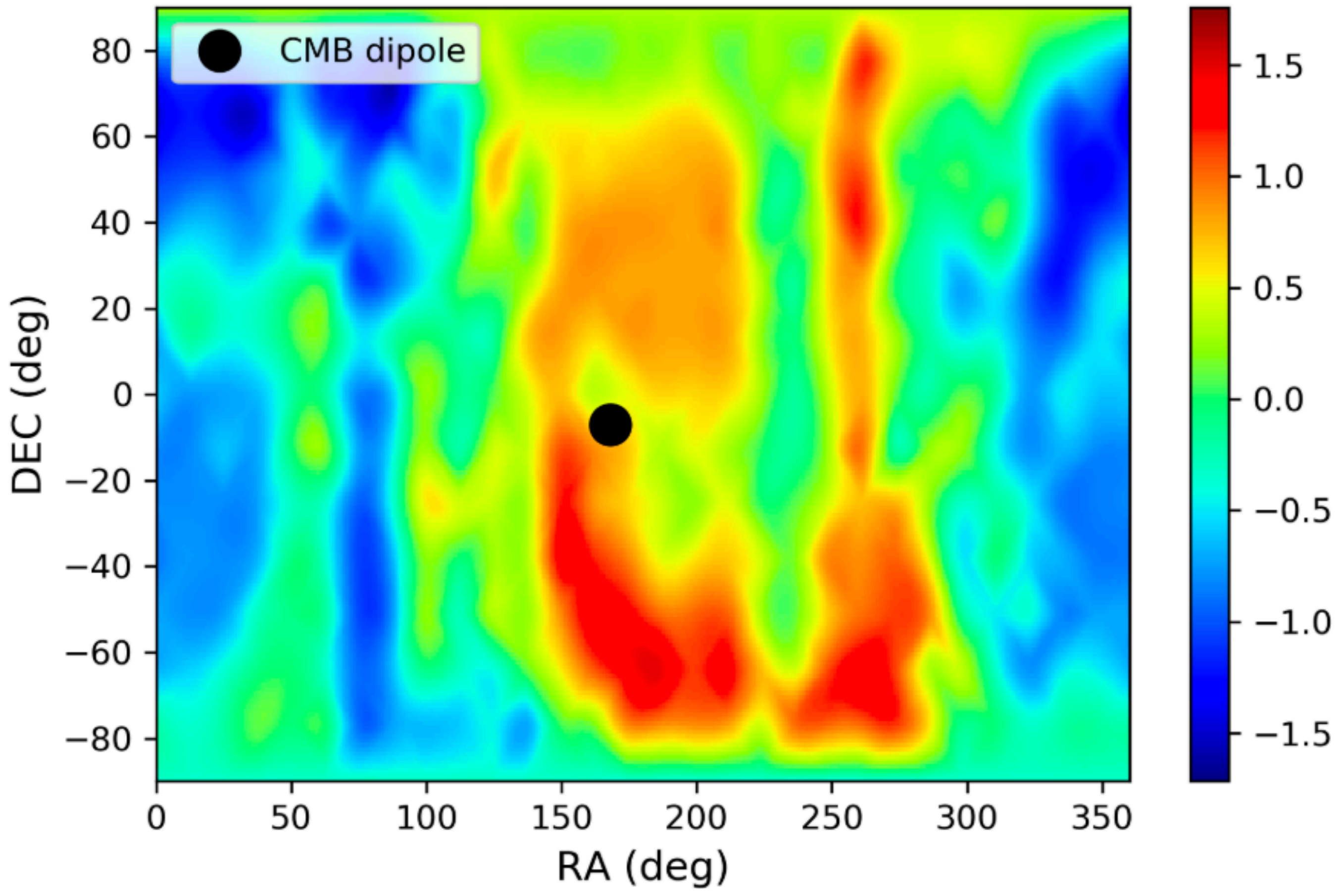
CMB dipole direction

H_0 direction dependence?
- Lx-T relation of X-ray clusters
- Followed by 9 other scaling relations

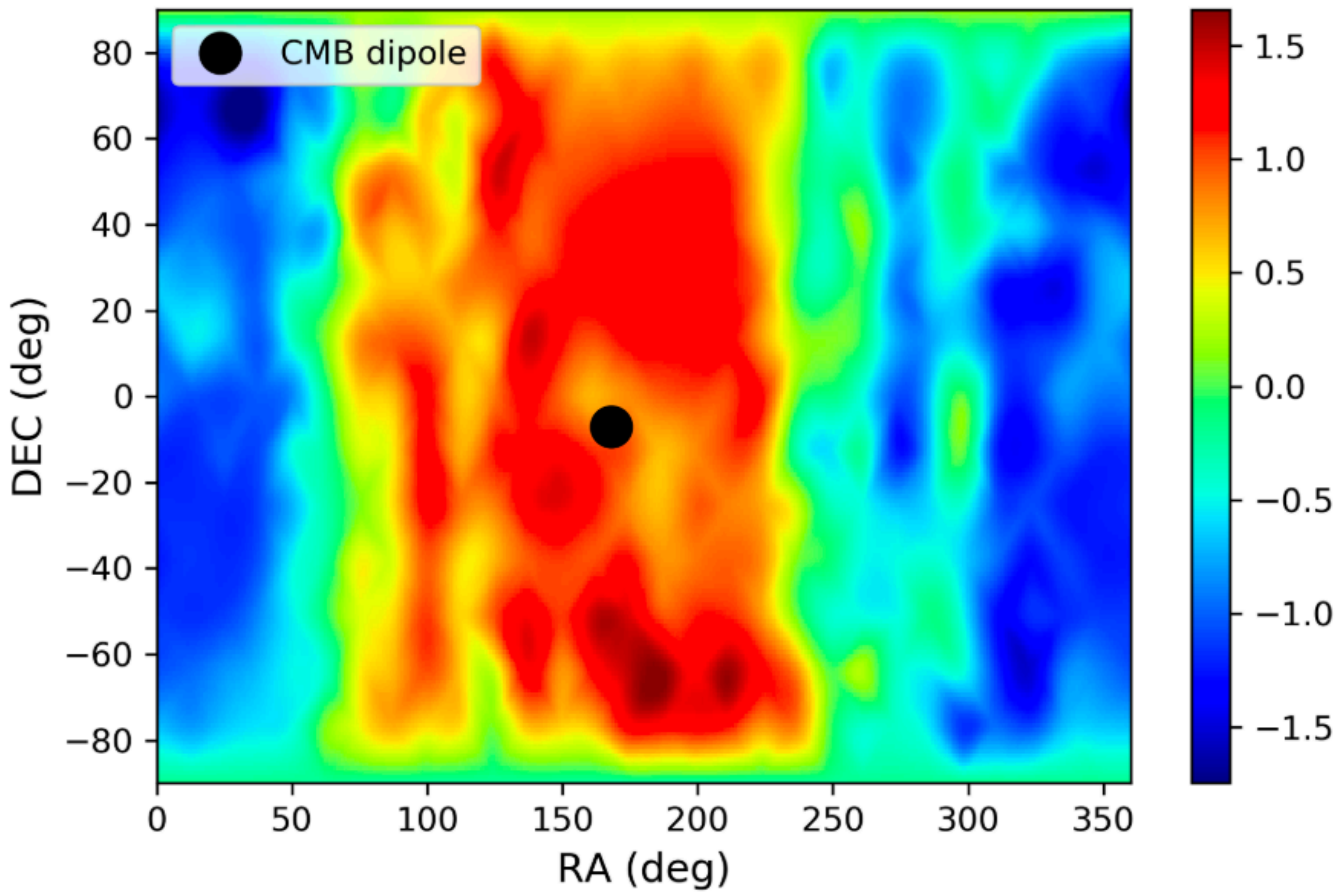
Larger H_0 in CMB dipole direction?
- Larger $\beta \sim H_0$ larger
- L_x-L_{UV} relation of QSOs
- Similar result from Amati correlation of GRBs [Amati+2008]

[Krishnan+ 2021a,b]
Hints of FLRW breakdown from SN
Discrepancy in H_0 correlated to CMB dipole

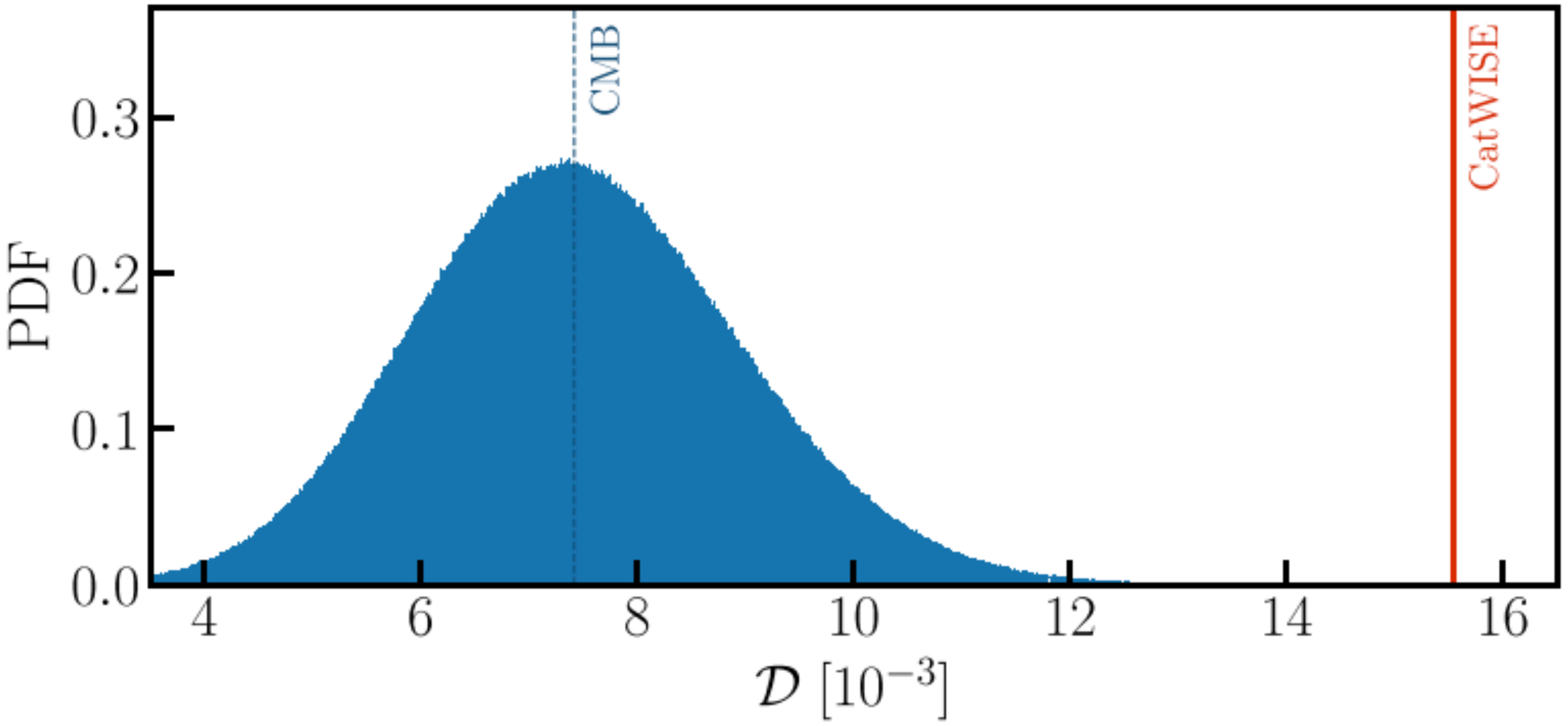
411 SN
z<0.2



1048 SN
0.01<z<2.26



[Secrest+ 2021](Fig.4)
Amplitude and direction of WISE QSO dipole
→ rejecting naively following CMB kinetic dipole interpretation
- Direction similar to CMB dipole
- Amplitude twice larger than expected $\sim 4.9\sigma$



The source of the CMB dipole:
- Apparent(Kinetic/Doppler boost)? Intrinsic cosmic dipole?
- Remains an open question [Planck 2018 LVI][Sullivan&Scott 2021]…

Why

- Possibility of cosmological principle breakdown (especially in late times)
- Deviation from homogeneity/isotropy suggested small in early time (CMB)
- The assumed component pervading the largest scales: dark energy (DE)
  $\Longrightarrow$ DE inhomogeneities?

What

- $\Lambda \to \phi(t)$ dynamics with CCP and dS Swampland
  $\to \phi(\mathbf{x}, t) = \phi_0(t) + \delta\phi(\mathbf{x}, t)$ inhomogeneities beyond cosmological principle
- Formulating dynamical DE with spatial inhomogeneities ϕ(x,t)

How

Extending the framework of standard perturbation theory with FLRW metric

- Late-time evolution of ϕ(x,t)
- Focus on the modification from inhomogeneities $\delta\phi(\mathbf{x}, t)$ to observable signals

2. SuperHorizon Isocurvature Dark Energy (SH-DE) setups

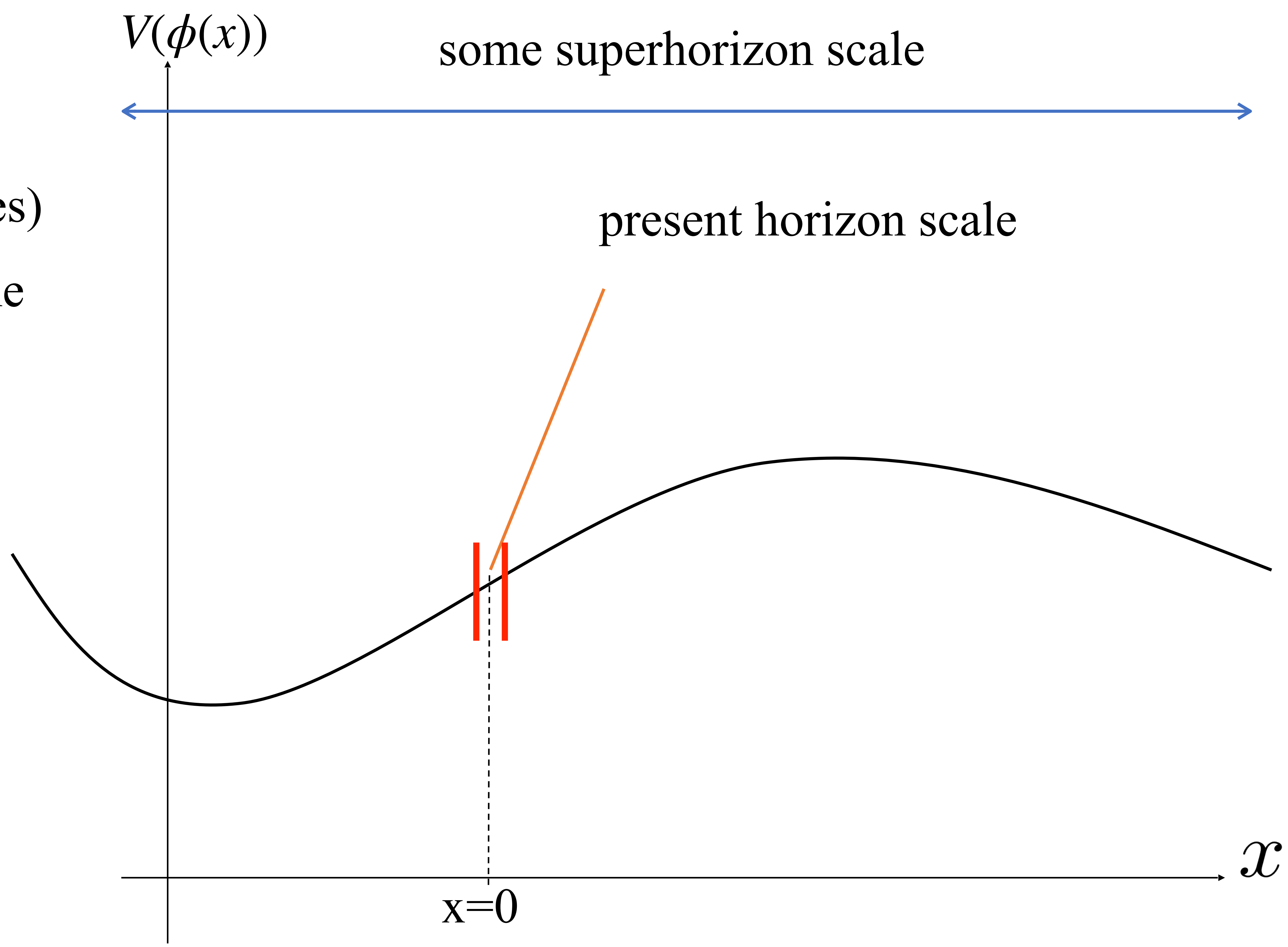
- Motivated by *supercurvature-mode dark energy*

[Nan+ 2019] ← [Aoki+ 2018]

- O(1) stochastic fluctuations of ultralight scalar field ϕ on supercurvature scale
  - $L_{sc} \gg L_c \gg L_H$
  - CDL bubble open universe $K = -1$ with inflaton $\psi_{inf.}$ (not ϕ)
- V(ϕ) drives late-time accelerated expansion (negligible spatial derivatives)
- Almost frozen in early time EoS $w \simeq -1$, thawing "slow-roll" in late time
- ***Isocurvature*** initial condition (for the interest of late-time)

(Generalized) ➥ SuperHorizon Dark Energy(SH-DE)

- For simplicity, let $K = 0$;ϕ dynamics with Hubble friction
- Thawing quintessence
- ***Isocurvature*** initial condition.
- O(1) Inhomogeneities on superhorzion scale.
  - $L_{sh} \gg L_H$
- Sh-mode: large-scale inhomogeneities of SH-DE
(slightly breaks cosmological principle on largest scales)



A schematic of sh-mode and horizon scale

- Digest of super curvature-mode DE

[YN, Kazuhiro Yamamoto, Hajime Aoki, Satoshi Iso, and Daisuke Yamauchi, 2019]

  - DE density contrast from quantum-origin random fluctuations

$$\delta(\eta, \boldsymbol{x}) = \frac{\rho_{\mathrm{DE}}(\eta, \boldsymbol{x}) - \langle \rho_{\mathrm{DE}}(\eta, \boldsymbol{x}) \rangle}{\langle \rho_{\mathrm{DE}}(\eta, \boldsymbol{x}) \rangle} \simeq \frac{\phi^2(\eta, \boldsymbol{x}) - \langle \phi^2(\eta, \boldsymbol{x}) \rangle}{\boxed{\langle \phi^2(\eta, \boldsymbol{x}) \rangle}}$$

L

$$R = \sqrt{-K}\,\boxed{|\boldsymbol{x} - \boldsymbol{y}|}$$

geodesic distance with curvature

$R_c = 1$

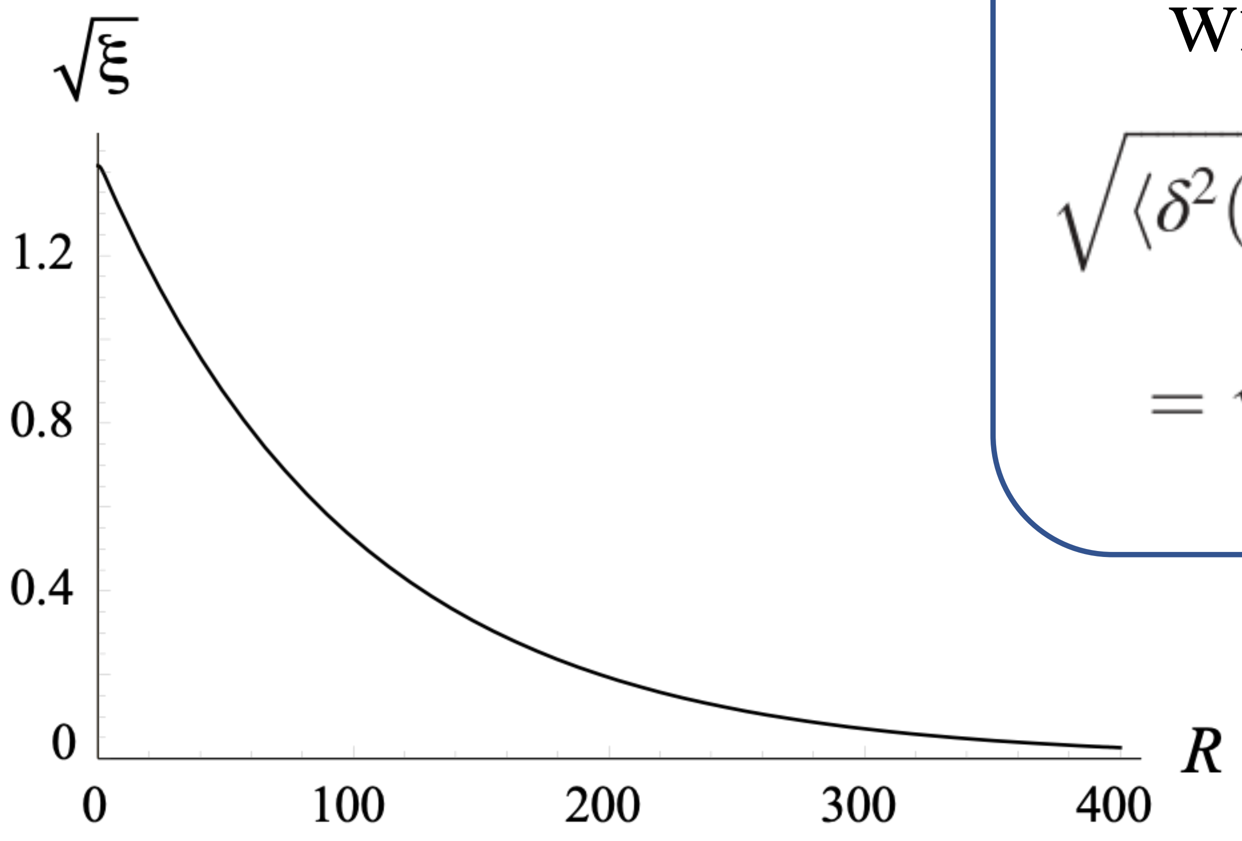
Curvature scale

  - 2PCF of density contrast

$\epsilon \ll 1$ Supercurvature condition in 2PCF of ϕ

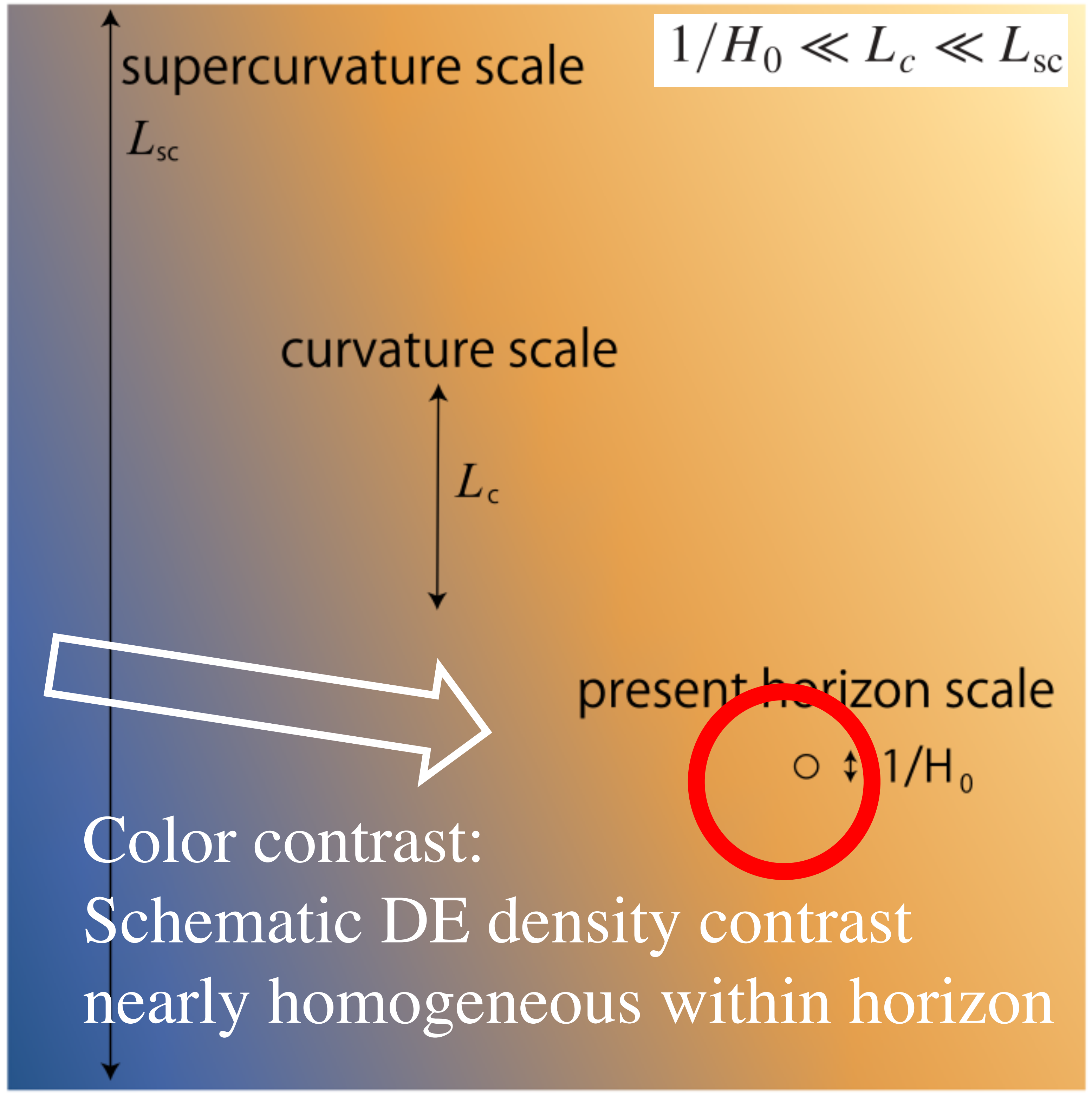
- ultralight field mass
- "frozen" EoS from time evolution $e^{-\epsilon\eta}$
- bound state energy [1st] (ancestor vac. bubble size)

$$\xi(R) \equiv \langle \delta(\eta, \boldsymbol{x}) \delta(\eta, \boldsymbol{y}) \rangle$$
$$= 2\left(\frac{\sinh(1-\epsilon)R}{(1-\epsilon)\sinh R}\right)^2 \simeq 2 \times \begin{cases} 1 & R \ll 1 \\ e^{-2\epsilon R} & R \gg 1 \end{cases}$$



- Forecasting inhomogeneities within horizon: small

$$\sqrt{\langle \delta^2(0) \rangle} - \sqrt{\langle \delta(0)\delta(1/H_0) \rangle}$$
$$= \sqrt{2} - \sqrt{2}\,\frac{\sinh(1-\epsilon)\sqrt{\Omega_K}}{(1-\epsilon)\sinh\sqrt{\Omega_K}} \simeq \sqrt{2}\,\frac{\epsilon\Omega_K}{3}$$



Formulation of the DE spatial inhomogeneities

- Flat late-time universe $\Omega_K = 0$
- Conformal Newtonian gauge

$$ds^2 = a^2(\eta)\left[-(1+2\Psi)d\eta^2 + (1+2\Phi)\delta_{ij}dx^i dx^j\right]$$

- Metric perturb. by the sh-modes inhomogeneities -> spatial multipoles

Matrices w.r.t. multipole expansion

$$\Psi = \epsilon_1 \sum_{m=1}^{3} \Psi_{1(m)}(\eta) \boxed{P_i^{(m)}} x^i + \epsilon_2 \sum_{m=1}^{5} \Psi_{2(m)}(\eta) \boxed{P_{ij}^{(m)}} x^i x^j$$

$$\Phi = \epsilon_1 \sum_{m=1}^{3} \Phi_{1(m)}(\eta) P_i^{(m)} x^i + \epsilon_2 \sum_{m=1}^{5} \Phi_{2(m)}(\eta) P_{ij}^{(m)} x^i x^j$$

$$\phi = \phi_0(\eta) + \epsilon_1 \sum_{m=1}^{3} \phi_{1(m)}(\eta) P_i^{(m)} x^i + \epsilon_2 \sum_{m=1}^{5} \phi_{2(m)}(\eta) P_{ij}^{(m)} x^i x^j$$

Background

$$\dot{\rho}_0 + 3H\rho_0 = 0$$

$$\ddot{\phi}_0(t) + 3H(t)\dot{\phi}_0(t) + m^2\phi_0(t) = 0$$

$$3H^2 = 8\pi G\left(\frac{1}{2}\dot{\phi}_0^2 + \frac{1}{2}m^2\phi_0^2 + \rho_0\right)$$

Perturbations(for ℓ = 1,2,3…)

$$\delta_1^{(n)} + 3\Phi_1^{(n)} = 0,$$

$$\dot{V}_1^{\prime(n)} - \Psi_1^{(n)} = 0,$$

$$\ddot{\phi}_1^{(n)} + 3H\dot{\phi}_1^{(n)} + m^2\phi_1^{(n)} + \left(3\dot{\Phi}_1^{(n)} - \dot{\Psi}_1^{(n)} - 6H\Psi_1^{(n)}\right)\dot{\phi}_0 - 2\Psi_1^{(n)}\ddot{\phi}_0 = 0$$

$$\Psi_1^{(n)} + \Phi_1^{(n)} = 0,$$

$$3H\left(\dot{\Phi}_1^{(n)} - H\Psi_1^{(n)}\right) = 4\pi G(\rho_0\delta_1^{(n)} + m^2\phi_0\phi_1 - \dot{\phi}_0^2\Psi_1^{(n)} + \dot{\phi}_0\dot{\phi}_1^{(n)}),$$

$$\dot{\Phi}_1^{(n)} - H\Psi_1^{(n)} = -4\pi G(\rho_0 V_1^{\prime(n)} + \dot{\phi}_0\phi_1^{(n)}),$$

- ℓ = 1,2 dipole , quadrupole ..
- ϵ_ℓ : order of amplitude for perturbations
  ←obs. constraint (e.g. ISW)
- General/extendable

Roughly

$$\epsilon^{\rm sh}\phi(t,\boldsymbol{x}) = \epsilon \underbrace{\sum_{n=1}^{3} \phi_1^{(n)}(t) T_i^{(n)} x^i}_{\text{dipole}} + \mathcal{O}(\epsilon^2 x^2)$$

Higher multipoles negligible for LSS at leading order

Background solution (+ perturbations)

- SH-DE EoS (c.f. CPL parametrization [M. Chevallier + 2001, E. Linder 2003])

$$\omega_\phi \equiv \frac{P_\phi}{\rho_\phi} = -\frac{m^2 a^2 \phi^2 - \dot{\phi}^2}{m^2 a^2 \phi^2 + \dot{\phi}^2} \equiv -1 + 2W(a)$$

At background level $\phi \to \phi_0$

$\boxed{\dot{\phi} \equiv \partial_\eta \phi \qquad \phi' \equiv \partial_a \phi}$

$$W(a) \equiv \frac{a^2}{(m_\phi/H)^2(\phi/\phi')^2 + a^2} = \frac{\tilde{\phi}_0'(a)^2 a^2 \tilde{H}(a)^2}{\tilde{m}^2 \tilde{\phi}_0(a)^2 + \tilde{\phi}_0'(a)^2 a^2 \tilde{H}(a)^2}$$

$$W(a) \simeq 1 - \frac{a\tilde{m}^2}{\Omega_m}\left(\frac{\tilde{\phi}_0^2}{\tilde{\phi}_0'^2}\right)\left(1 - \tilde{r}a^2\tilde{\phi}_0'^2\right)$$

$$\simeq 1 - \frac{a\tilde{m}^2}{\Omega_m}\left(\frac{\tilde{\phi}_0^2(a)}{\tilde{\phi}_0'^2(a)}\right),$$

Small kinetic terms

$$\boxed{\omega_\phi(a) \simeq -1 + 2\left(1 - (a\tilde{m}^2\tilde{\phi}_0^2)/(\Omega_m \tilde{\phi}_0'^2)\right)}$$

$$\tilde{H}(a) = \sqrt{\frac{\tilde{r}\tilde{m}^2\tilde{\phi}_0^2 + \Omega_m a^{-3}}{1 - \tilde{r}a^2\tilde{\phi}_0'^2}}$$

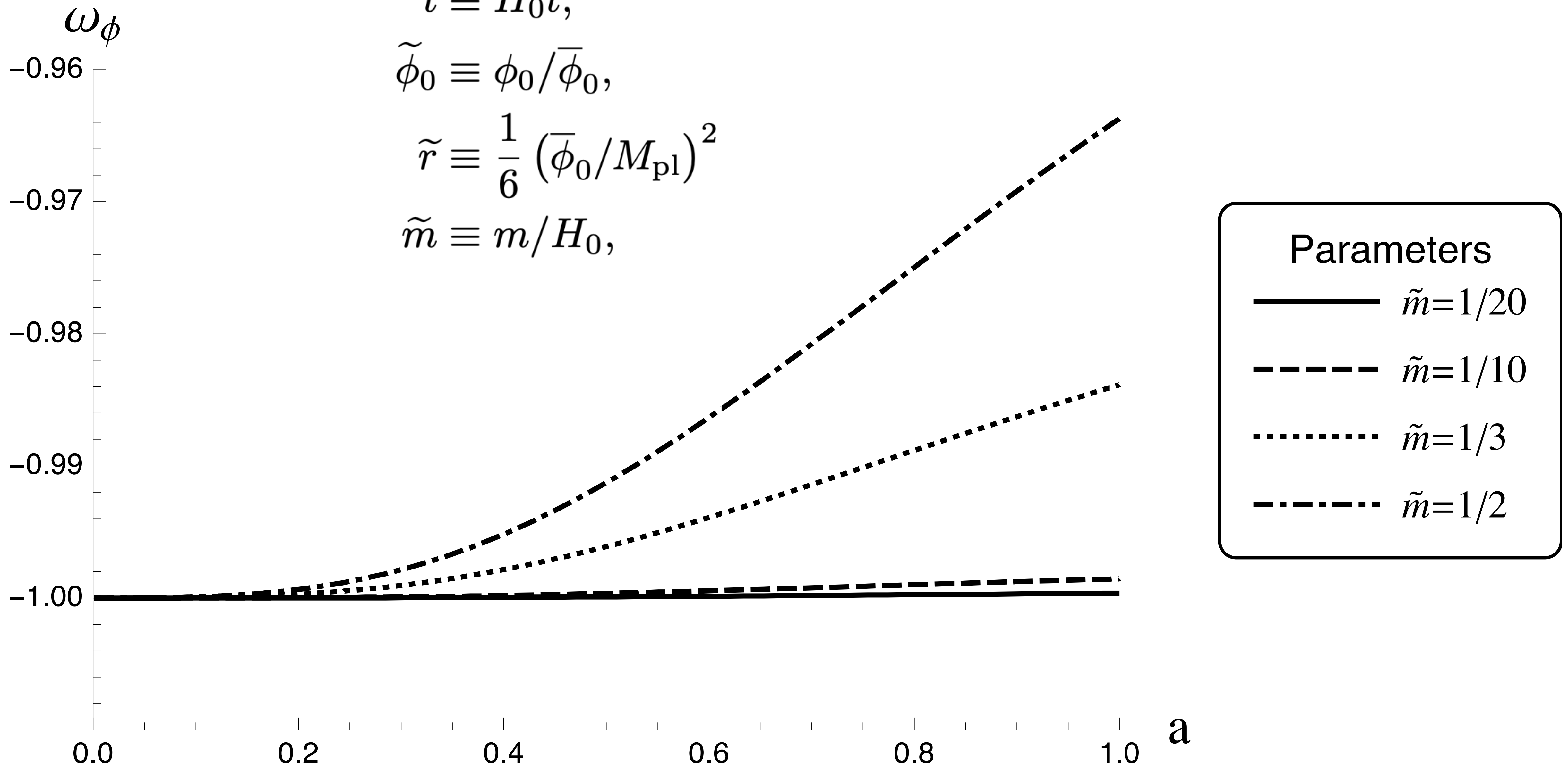
Background Expansion Rate

(a<1)

$$\tilde{H}(a) \simeq \sqrt{(1-\Omega_m)\tilde{\phi}_0^2 + \Omega_m a^{-3}}$$

Non-dimensional parameters

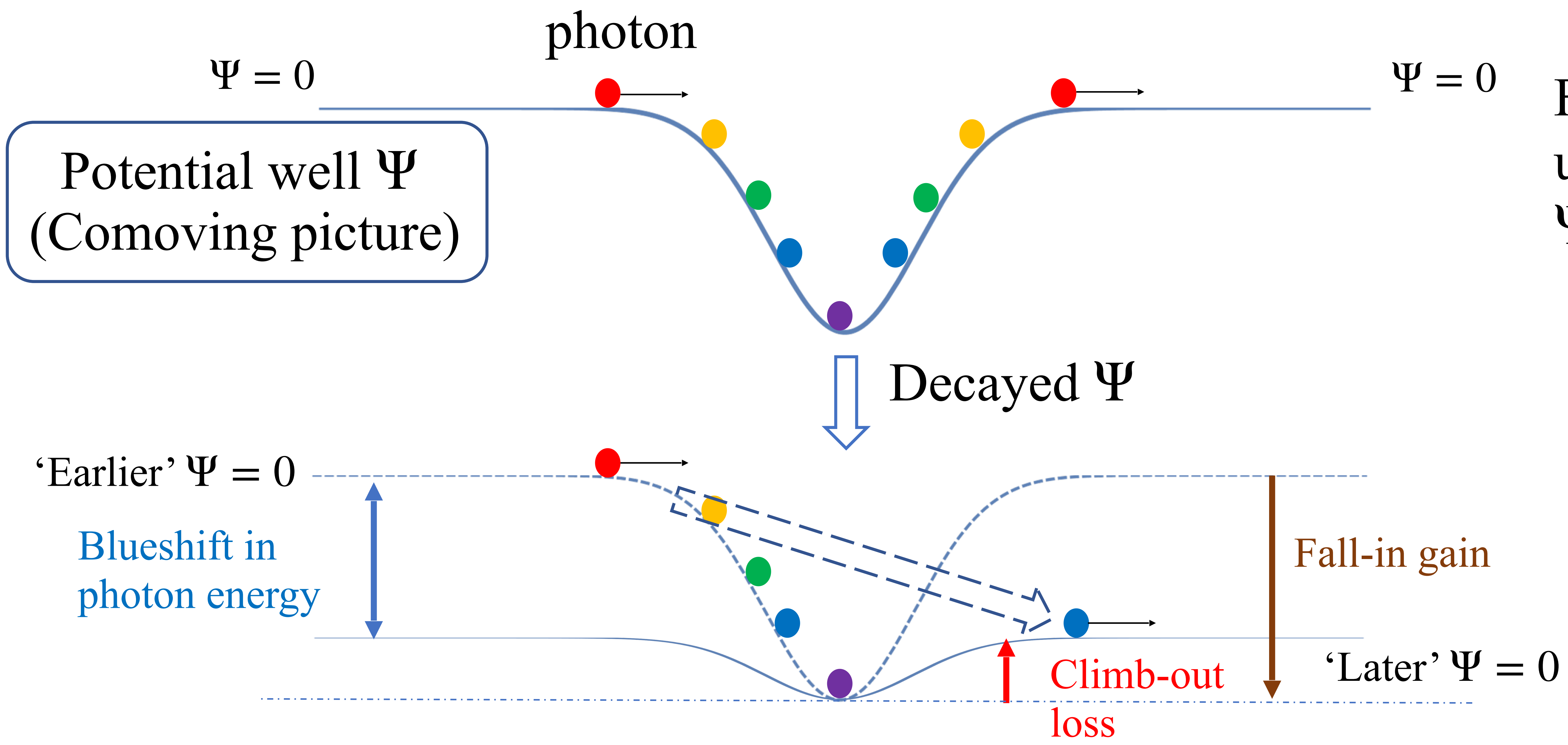
$$\tilde{t} \equiv H_0 t,$$
$$\tilde{\phi}_0 \equiv \phi_0/\bar{\phi}_0,$$
$$\tilde{r} \equiv \frac{1}{6}\left(\bar{\phi}_0/M_{\rm pl}\right)^2$$
$$\tilde{m} \equiv m/H_0,$$



- $\tilde{m}^2$ typically small & important for
  - Late-time dynamics of ϕ
  - Future expansion H(a) (a>>1)
- $\tilde{r}$: not important for dynamics and EoS in late time (related to the energy scale of ϕ)

EoS of DE w(a) high z (small a) : DES, DESI, PFS, Euclid, LSST-DESC, WFIRST ..
→Testable with data as a *thawing model* with CPL parametrization

DE probe: late-time Integrated Sachs-Wolfe (ISW) effect



For pure-matter universe EoS w=0 $\Psi = \text{const}$.

With Ω_Λ, 'total' EoS w changes, Ψ decays as photon travels (takes time)

- Photon energy shift <-> obs. CMB temperature shift

$$\boxed{\frac{\Delta T}{T} \sim 2 \int \frac{\partial \Psi}{\partial \eta} \mathrm{d}\eta}$$

Integration over time
(isocurvature perturb.)

- Notice: focus on Ψ from superhorizon isocurvature modes: independent from & additional to normal adiabatic mode ISW contributions.

CMB anisotropies via late-time ISW by SH-DE

CMB anisotropies via ISW (Similar for random field handling in ScmDE)

$$\begin{cases} \dfrac{\Delta T}{T} \simeq 2\displaystyle\int_{\eta_d}^{\eta_0} \mathrm{d}\eta \left(\frac{\partial\Psi(\eta,\chi)}{\partial\eta}\right)\Bigg|_{\chi=\eta_0-\eta} \equiv 2\sum_{\ell=1}^{2} \epsilon_\ell Q_{\ell(m)} Y_\ell^{(m)}(\theta,\varphi) \\ \dfrac{\Delta T}{T} = \displaystyle\sum_\ell \sum_m A_{\ell m} Y_\ell^{(m)}(\theta,\varphi) \end{cases}$$

induced by DE inhomogeneities

$$\boxed{Q_{\ell(m)} \equiv Q_\ell \equiv \int_{\eta_d}^{\eta_0} \mathrm{d}\eta(\eta_0-\eta)^\ell \frac{\partial\Psi_\ell}{\partial\eta}}$$

- close to ΛCDM parameters $\boxed{\tilde{r}\tilde{m}^2 = 1-\Omega_m}$ $\xrightarrow{\text{Numerical calc.}}$ $Q_1 = -1.1\times 10^{-1}$, $Q_2 = -9.0\times 10^{-2}$

- Constraint from obs.

$$\langle |A_{\ell m}|^2\rangle \leqslant \boxed{C_\ell^{\mathrm{obs}}} \Rightarrow \boxed{\begin{aligned}\epsilon_1 &\leq 1.2\times 10^{-2}\\ \epsilon_2 &\leq 5.7\times 10^{-5}\end{aligned}} \Leftrightarrow \boxed{\begin{aligned}\epsilon\Omega_K &\lesssim 4.9\times 10^{-5}\\ \epsilon\Omega_K^2 &\lesssim 1.0\times 10^{-8}\end{aligned}}$$

ScmDE

Other parameter cases checked too

- Consistency with ScmDE if $\Omega_K \sim 10^{-3}$, $\epsilon \lesssim \mathcal{O}(10^{-2})$.
- Applicable when $\Omega_K \to 0$ in flat case, though physical model and initial conditions before MD for ultralight scalar field ϕ need exploration

Perturb. to luminosity distance

- Perturbation to Luminosity distance with flat approximation K=0 [M. Sasaki 1987]

$$I \equiv \frac{\delta d_L}{d_L}$$

$$\equiv \sum_{\ell=1}^{2} \epsilon_\ell S_{\ell(m)} Y_\ell^{(m)}(\theta, \varphi)$$

- Light propagation parameter
  $\lambda = \eta_0 - \eta = \chi$
- Index 's': light source

Traceless matrix of the multipoles $\Delta^{(3)}\Psi = 0$

$\sim\mathcal{O}(\varepsilon_\ell)$ Amplitude of perturbations (constraint by obs. from ISW)

$$S_{\ell(m)} \equiv \int_0^{\chi_s} \mathrm{d}\chi \frac{\chi - \chi_s}{\chi_s} \left(\chi^{\ell+1} \ddot{\Psi}_{\ell(m)} - 2\ell \chi^{\ell} \dot{\Psi}_{\ell(m)} \right) = F_{S\ell(m)}(a) \mathcal{D}_{(\ell m)}$$

Contributions induced by DE inhomogeneities

Function of a or z (sources from different epochs)

Multipole components for I

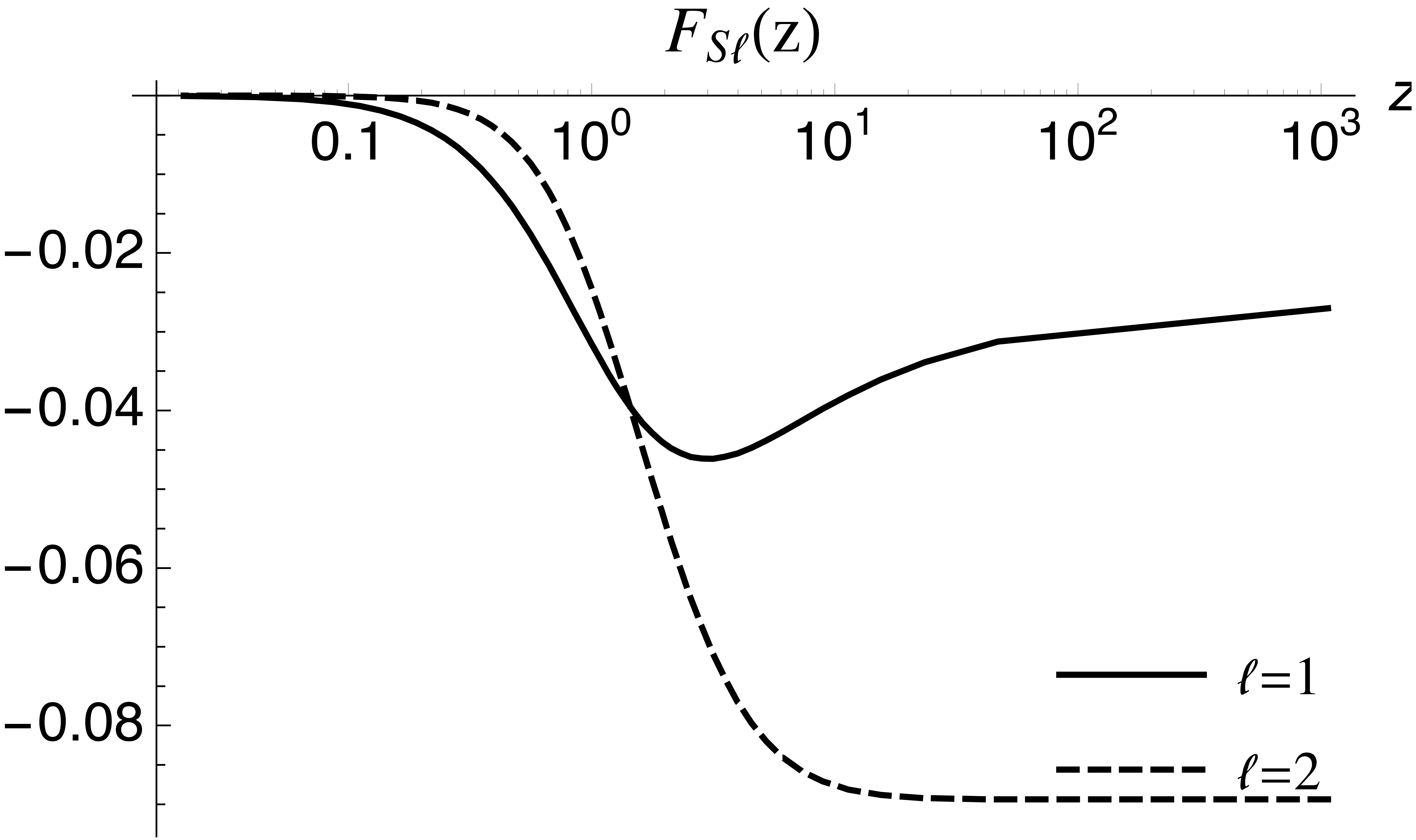
$$I_\ell \equiv \sum_{m=1}^{2\ell+1} S_{\ell(m)}$$

dipole ℓ=1 $\mathcal{O}(10^{-3})$

quadrupole ℓ=2 $\mathcal{O}(10^{-5})$

- evaluated at z=3
- for typical values of parameters (all models in Table)

Not big enough to account for luminosity distance anisotropy?
(Appropriate parameters? Spatial derivative terms?)



- Correction from the dipole ($\ell = 1$) seem to have maximum around z~3
- May be interesting for future surveys planned to focus near this redshift.

Description of LSS modificaiton by sh-mode with SH-DE

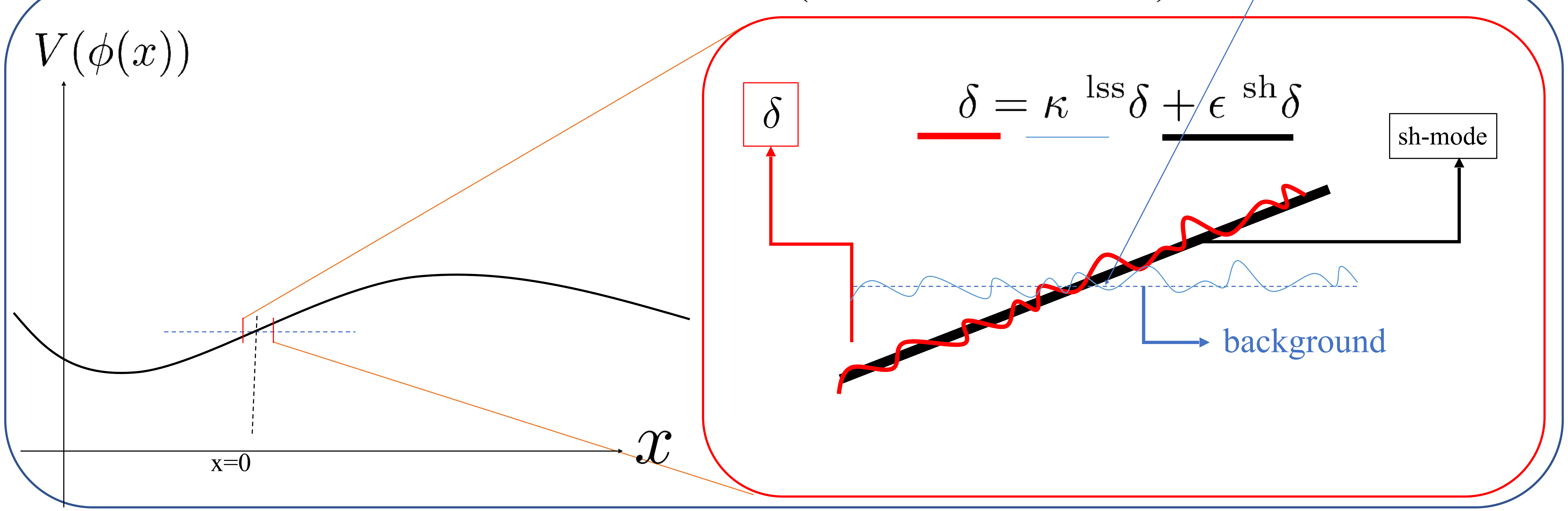
Small expansion-order parameters for perturb.
κ: SPT (linear up to $\mathcal{O}(\kappa)$)
ϵ: SH-DE/sh-mode induced perturb.

- Focus on modification from DE inhomogeneities

matter density	$\rho = \rho_0(1+\delta)$
(m) density fluc.	$\delta = \kappa\,{}^{\rm lss}\delta + \epsilon\,{}^{\rm sh}\delta$
velcity field	$v^i = \kappa\,{}^{\rm lss}v^i + \epsilon\,{}^{\rm sh}v^i$
curvature potential	$\Psi = \kappa\,{}^{\rm lss}\Psi + \epsilon\,{}^{\rm sh}\Psi$
grav .potential	$\Phi = \kappa\,{}^{\rm lss}\Phi + \epsilon\,{}^{\rm sh}\Phi$

LSS perturbations (short wavelength compared with sh-mode)

sh-mode & lss-mode(ad-mode+ iso-mode)



Lss-mode : ad-mode & iso-mode

${}^{\rm ad}\delta$: density perturb. with standard scenario
${}^{\rm iso}\delta$: sh-mode induced correction to density perturb ${}^{\rm ad}\delta$ (isocurvature initial condition)
- 'short' wavelength scale compared with sh-mode ($L_{lss} \ll L_{sh}$)

- 2 parameter expansion up to $\mathcal{O}(\kappa\epsilon)$
- Coupling of iso-mode & ad-mode on LSS

$$\kappa\ {}^{\rm lss}\delta = \kappa\left({}^{\rm ad}\delta + \epsilon\ {}^{\rm iso}\delta\right) \qquad ({}^{\rm lss}v, {}^{\rm lss}\Psi, {}^{\rm lss}\Phi)$$

Continuity Eq.
Euler Eq.
with linear PT

$$\frac{\partial\rho}{\partial t} + 3H\rho + \frac{1}{a}\partial_i(\rho v^i) + 3\dot{\Phi}\rho = 0$$

$$\frac{\partial}{\partial t}(\rho v^i) + 4H\rho v^i + \frac{1}{a}\partial_j(\rho v^i v^j) + \frac{\rho}{a}\frac{\partial\Psi}{\partial x^i} + 4\dot{\Phi}\rho v^i = 0$$

$${}^{\rm iso}\ddot{\delta}_\kappa(t,\vec{p}) + 2H\,{}^{\rm iso}\dot{\delta}_\kappa(t,\vec{p}) - 4\pi G\rho_0\ {}^{\rm iso}\delta_\kappa \equiv \boxed{S_\delta(t,\vec{p})}$$

Source term due to sh-mode ad-mode coupling

isocurvature initial condition

$$t=0 \qquad {}^{\rm sh}\Phi(0,\boldsymbol{x}) = {}^{\rm sh}\Psi(0,\boldsymbol{x}) = 0$$

$$\epsilon\ {}^{\rm sh}v^i \simeq \epsilon\sum_{n=1}^{3} V_1^{(n)}(t)T_i^{(n)}$$

$$\epsilon\ {}^{\rm sh}\delta \simeq \epsilon\sum_{n=1}^{3} \delta_1^{(n)}(t)T_i^{(n)}x^i$$

$$\epsilon\ {}^{\rm sh}\Phi \simeq \epsilon\sum_{n=1}^{3} \Phi_1^{(n)}(t)T_i^{(n)}x^i$$

Considering dipole neglecting higher

Sol. of iso-mode(lss-mode) ${}^{\rm iso}\delta$, ${}^{\rm lss}\delta$
for LSS power spectrum formulation/evaluation

Density fluctuation and power spectrum with the iso-mode

$$ {}^{\mathrm{lss}}\delta = {}^{\mathrm{ad}}\delta_\kappa + \epsilon\,{}^{\mathrm{iso}}\delta_\kappa = D_1(a)\delta_L(\vec{p}) + \epsilon D_1(a)\delta_L(\vec{p})\frac{2}{5}\sqrt{\frac{3}{4\pi}}\frac{(ip)}{H_0\sqrt{\Omega_m}}\boxed{(\mathcal{I}(a) - \mathcal{J}(a))}\cos\theta $$

Direction of intrinsic dipole of SH-DE: $e^{(n)}$

$$ \sum_{n=1}^{3} k^n e^{(n)} = |k|\cos\theta $$

$$ \mathcal{I}(a) \equiv \frac{D_2(a)}{D_1(a)}\int_0^a da' D_1(a')\mathcal{G}(a') $$

$$ \mathcal{J}(a) \equiv \int_0^a da' D_2(a')\mathcal{G}(a') $$

Modification kernel of growth due to ad-mode & iso-mode coupling $\mathcal{O}(\kappa\epsilon)$

$$ \mathcal{G}(a) \equiv D_1(a)\left\{ V_1(a)\left[2f(a) + 1\right] + a\frac{\mathrm{d}V_1(a)}{\mathrm{d}a} \right\} $$

Modified power spectrum with SH-DE

$$ P(a,k,\theta) = P_0(a,k)\left(1 + \epsilon^2 k^2 \cos^2\theta\,\mathcal{R}(a)\right) $$

Time evolution of modification

$$ \mathcal{R}(a) = \frac{3}{25\pi}\frac{1}{\Omega_m H_0^2}\left(\mathcal{I}(a) - \mathcal{J}(a)\right)^2 $$

Relative modification to the standard Power spectrum

$$ \xi_{\mathrm{modif}}(k,\theta,a) \equiv \epsilon_{\max}^2 k^2 \cos^2\theta\,\mathcal{R}(a) \propto k^2 $$

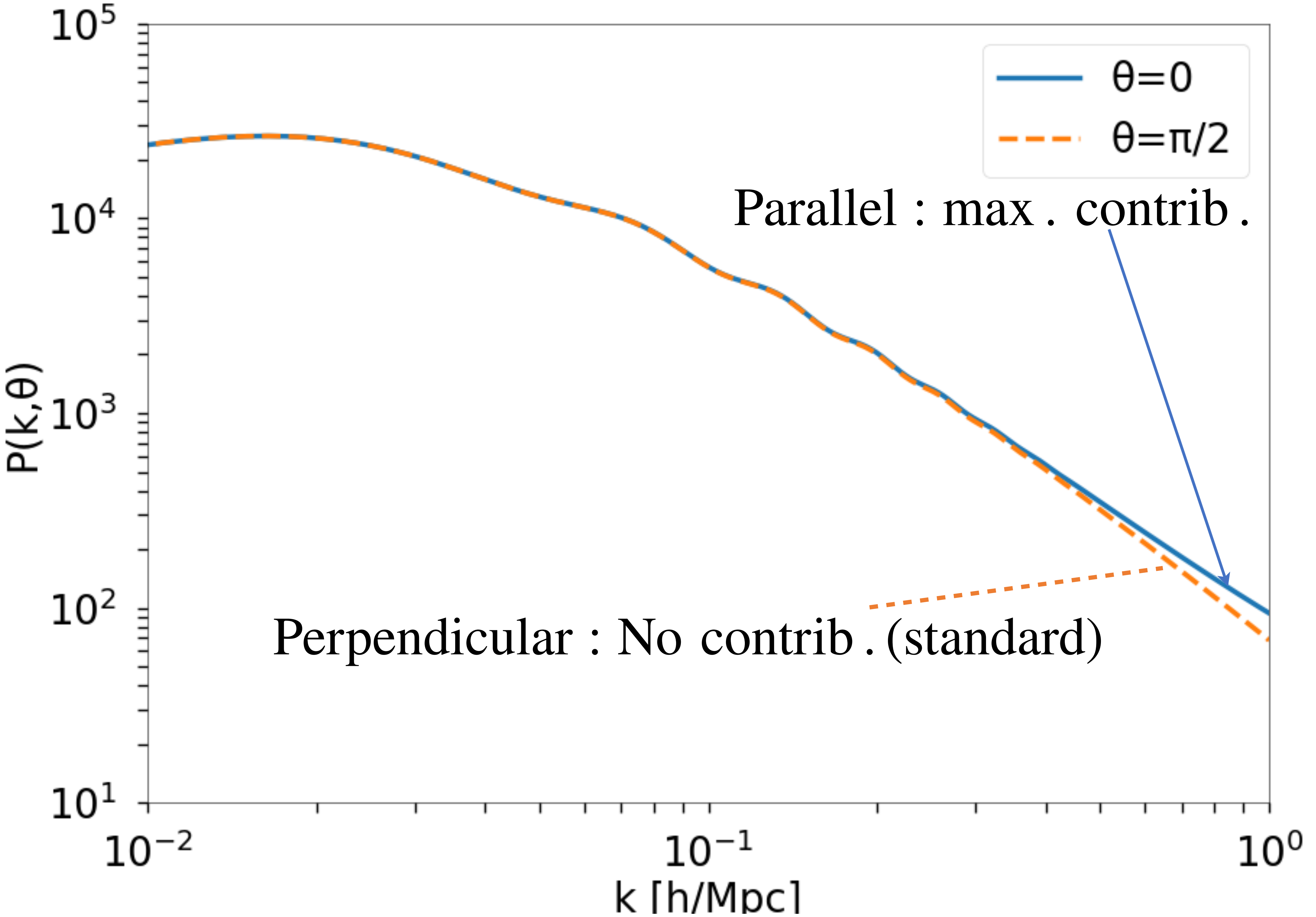
$P_0 = D_1^2 P_m(k)$ 'Standard' Power spectrum of homogeneous universe

F : initial value of ϕ to fix its density with dynamics

Model	$\tilde{r}$	$\tilde{m}$	F	Ω_m	ϵ_{max}	$J_1^{(n)}$
No. 1	70	1/10	1.00	0.30	0.0117	0.107
No. 2	6.3	1/3	1.01	0.30	0.0117	0.107
No. 3	72	1/10	1.00	0.28	0.0108	0.116
No. 4	68	1/10	1.00	0.32	0.0127	0.0985

J_1 ISW contribution to CMB due to SHDE

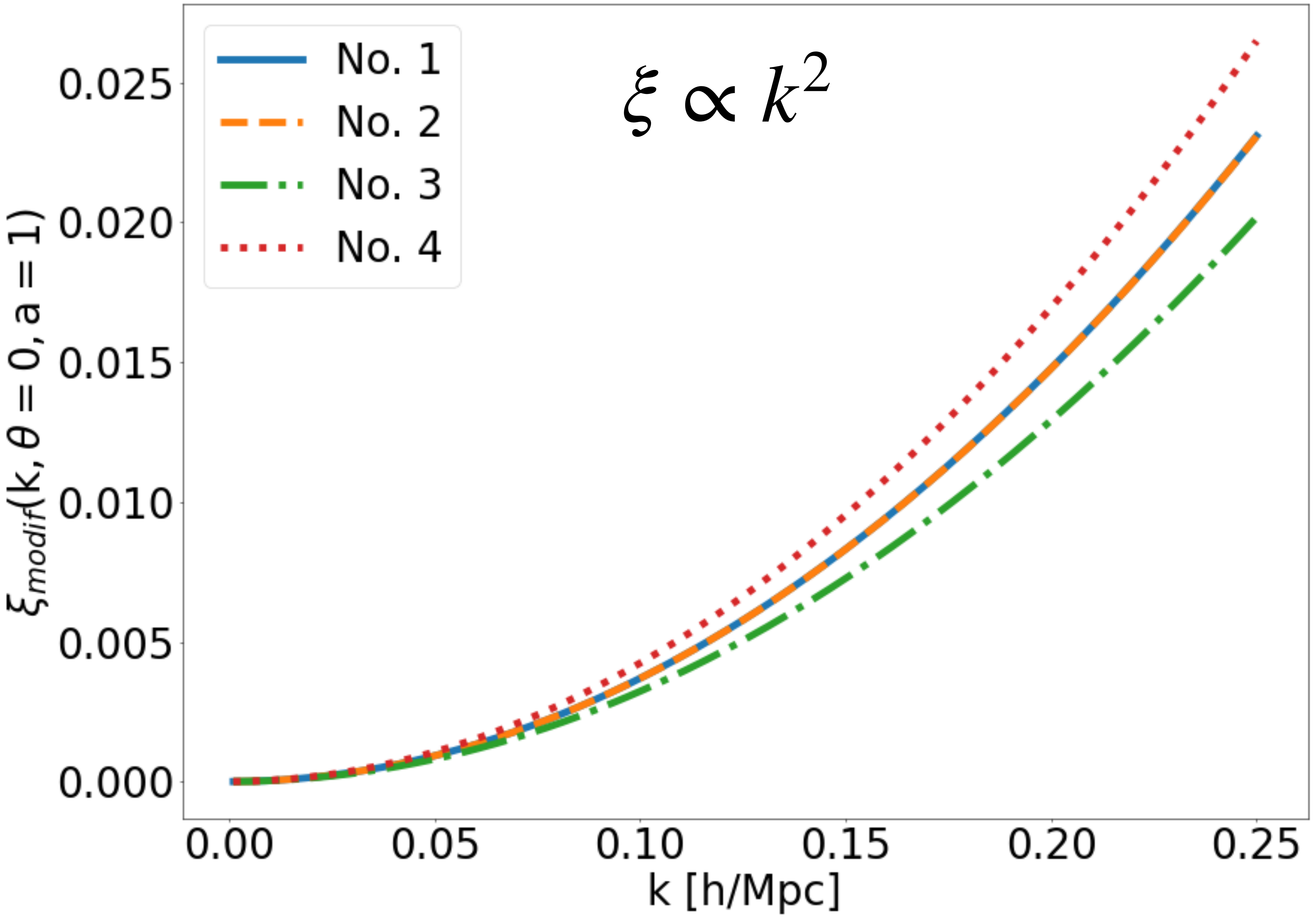
ϵ_{max} maximum amplitude inferred from CMB



Modification to the standard matter power spectrum (Directional-dependent)

For $P(a=1,k)$

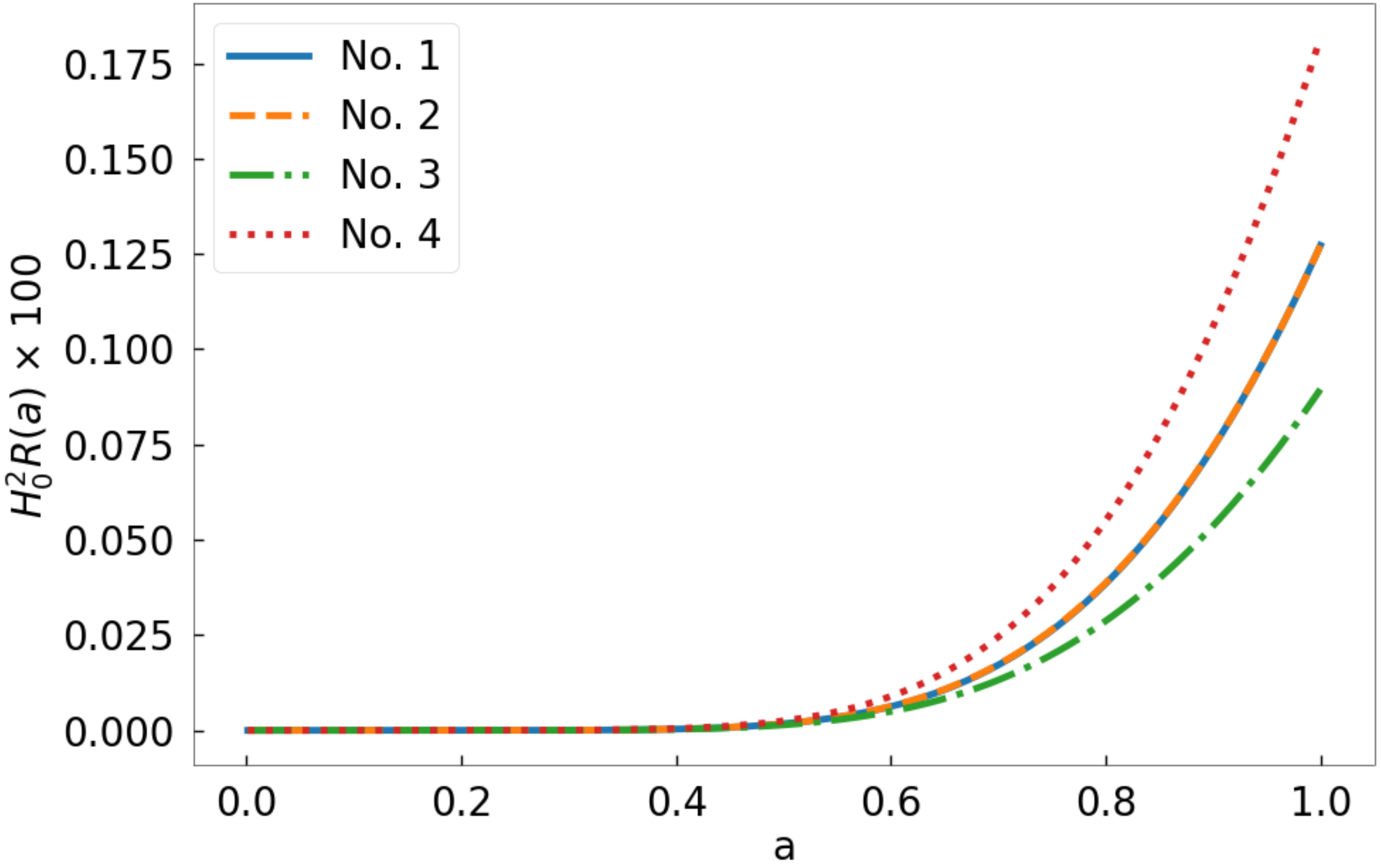
- $\tilde{m}, \tilde{r}$ unimportant for power spectrum (DE dynamics)
- Dipole amplitude ϵ and $\Omega_m(\Omega_\phi)$ important



~1% correction up to k~0.15 hMpc-1 with direction dependency

Modification to standard matter power spectrum

Time evolution of modification



$$P(a,k,\theta) = P_0(a,k)\left(1 + \epsilon^2 k^2 \cos^2\theta \mathscr{R}(a)\right)$$

Modification to σ_8

$$^{\mathrm{sh}}\sigma_R^2(a,\theta) = \frac{1}{2\pi^2}\int_0^\infty \mathrm{d}k k^2 P(a,k,\theta) W^2(kR)$$

$$^{\mathrm{sh}}\sigma_8 \sim 0.825 + 0.008$$

1 % correction

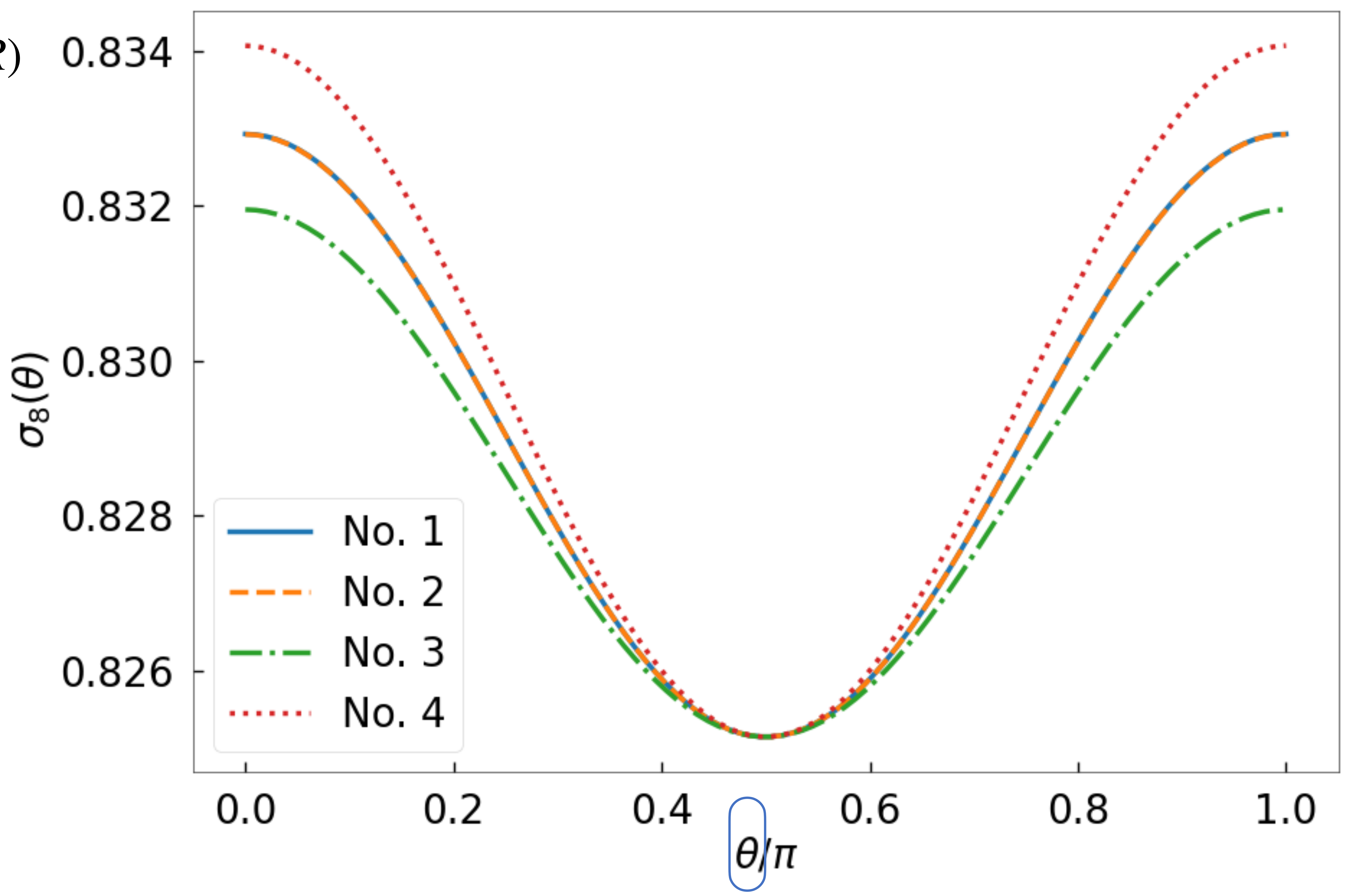
[Pandley+ 2020]

Planck $\rightarrow \sigma_8 = 0.829 \pm 0.015$

SDSS $\rightarrow \sigma_8 = 0.785 \pm 0.044$

[More+ 2015]

…. whose system errors are still large to test the model or draw a conclusion



Summary

- A general formulation of DE with spatial inhomogeneities
- Formulation of the prediction of the modifications to observables (e.g., CMB TT low multipole via ISW, luminosity distance, LSS matter power spectrum…)

- Some results:
  - Theoretical prediction of SH-DE based matter power spectrum : 1% correction up to k~0.15hMpc^{-1}
  - Estimation on correction to σ_8 maximum 1 % correction depending on the direction
  - Density fluctuation of LSS-mode barely depends on $\tilde{r}, \tilde{m}$ parameters of SH-DE (Dynamics of DE barely affects DM in this model, only interaction via. grav.)
  - The amplitude of initial fluctuations ϵ & Ω_m are important for the effect of modification

To go further

- Full Prediction on CMB TT anisotropies from photon geodesic
- Formulation beyond FLRW metric
  multipole expansion of the scale factor expansion rate $H(\mathrm{x})$ c.f. [Kalbouneh+ arXiv:2210.11333]
  Breaking cosmological principle: intrinsic dipole cosmology c.f. [Krishnan+ arXiv:2209.14918]

Possibly

- Early-time modeling
- Cosmic birefringence? [Y. Minami & E. Komatsu 2020]
  on ALPs [T. Fujita+ 2021]
- Growth history: $f\sigma_8(a)$ tomography as a probe
- Understanding small-scale modification (beyond $\propto k^2$) due to iso-mode & ad-mode coupling

  Now: Formulation validity up to $k \sim 0.2h\mathrm{Mpc}^{-1}$ with linear SPT
  - Analytic extension of the model in quasi-linear & nonlinear regimes (with halo/bias tracers)
  - 'Separate universe' simulation in view of super-sample mode [R. Terasawa+ 2022]

Thank you

for attending!