Title: Axionic Blue Isocurvature Perturbations: Generation and Astrophysical Detection Forecasts

Speakers: Sai Chaitanya

Series: Cosmology & Gravitation

Date: February 08, 2024 - 11:00 AM

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Abstract: When additional degrees of freedom are considered during inflation, a crucial aspect of early universe physics emerges: the generation of isocurvature quantum fluctuations. In this talk, we will present generation and detection forecast for axionic blue-tilted isocurvature power spectra. The large blue-tilt readily evades current CMB bounds. Following a brief review, we will discuss a SUSY-embedded axion model which generates a strongly blue tilted (nI~4) isocurvature spectrum during inflation when the quantum modes are starting to be underdamped (m/H > 3/2). Interestingly, there exist parametric regions with strong resonant spectral behavior that lead to rich isocurvature spectral shapes and large amplitude enhancements. These can be particularly interesting with observational consequences, in relation to the generation of PBH and GWs. The isocurvature spectral tilt is directly linked to the axion mass during inflation. Detecting blue-tilted isocurvatures can offer indirect evidence of a weakly interacting dark matter-like spectator field beyond conventional thermal-relic scenarios. Lastly, we will examine and forecast constraints for experiments such as Euclid (upcoming) and MegaMapper (proposed) using EFTofLSS based perturbative techniques. In the process we will comment upon the consistent renormalization requirements for mixed adiabatic and blue isocurvature primordial spectra.

Zoom link

AXIONIC BLUE ISOCURVATURES AND FORECAST USING EFT-OF-LSS

Tadepalli Sai Chaitanya

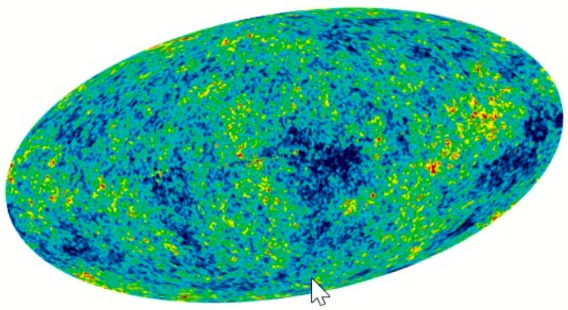
with Profs. Daniel Chung and Moritz Muenchmeyer

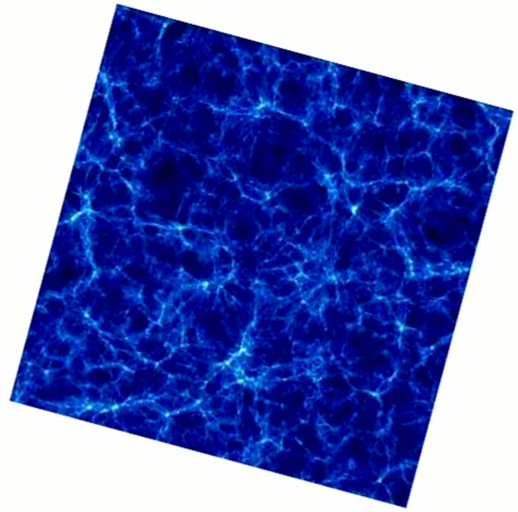
THE UNIVERSITY of WISCONSIN MADISON

February 08, 2024

Isocurvature Perturbations [2110.02272, 2309.17010]

$$S_{ij} = 3\left(\zeta_i - \zeta_j\right)$$





Adiabatic	Isocurvature
single dynamical mode	Multiple independent dynamical modes

$$\delta_c^{\rm ad} = \delta_b^{\rm ad} = \frac{3}{4}\delta_\gamma^{\rm ad} = \frac{3}{4}\delta_\nu^{\rm ad}$$

$$\delta_c^{\rm iso} = \delta_c - \delta_c^{\rm ad} = \delta_c - \frac{3}{4}\delta_\gamma^{\rm ad}$$

Matter-Radiation isocurvature quantity

$$\zeta = \Phi^{\mathrm{N}} - H\frac{\delta\rho^{\mathrm{N}}}{\dot{\rho}}$$

$$\boxed{S = \frac{\delta\rho_m}{\rho_m} - \frac{3}{4}\frac{\delta\rho_r}{\rho_r} = \delta_m - \frac{3}{4}\delta_r.}$$

Adiabatic		Isocurvature
$\zeta_i = \zeta_j$	Gauge-invariant definition	$S_{ij} = 3\,(\zeta_i - \zeta_j)$
$\Phi \neq 0, S = 0$	Initial conditions for solving fluid equations	$\Phi = 0, S \neq 0$

Given N dofs: we can classify them as 1 “adiabatic” and N-1 “isocurvature”.

Isocurvature spectrum

$$\Delta^2_{S_\chi}(k) \sim k^3 \int d^3k' \left\langle S_{\chi,\gamma,\vec{k}} S_{\chi,\gamma,\vec{p}} \right\rangle \sim k^{n_I - 1}$$

$$n_I - 1 = 3 - 2\sqrt{9/4 - m_\chi^2/H^2}$$

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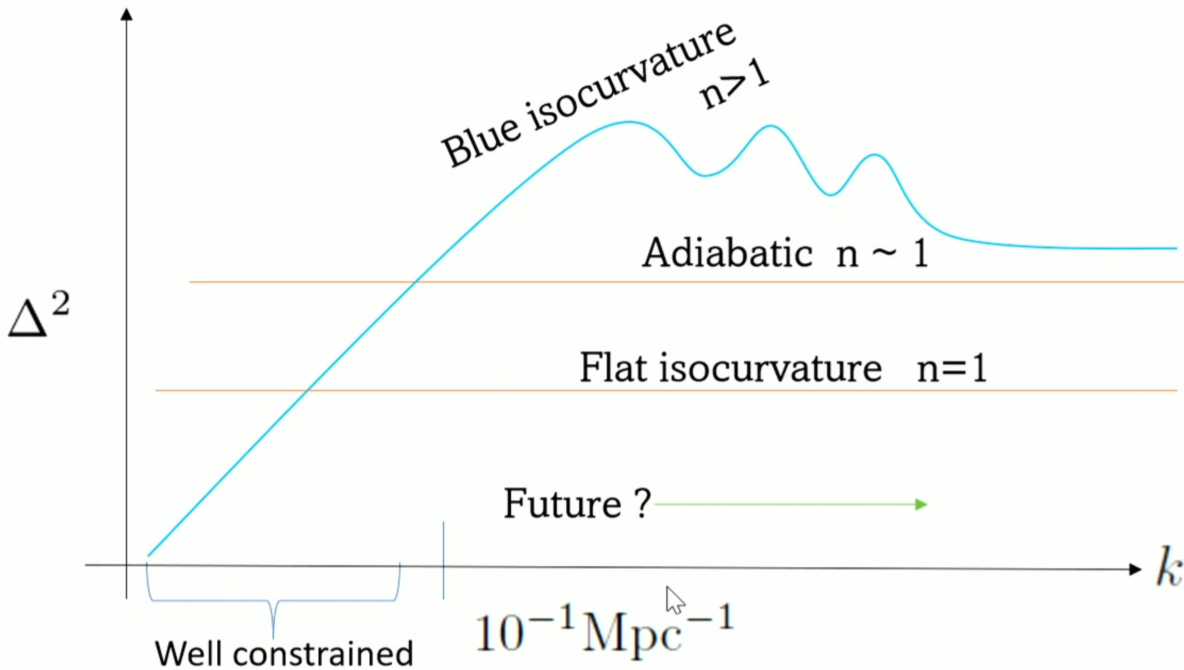
Currently, scale invariant isocurvature perturbations are observationally constrained to be less than 2% on large (CMB) scales at k=0.05/Mpc. [**1807.06211**]



$$\Delta^2(k) \sim k^{n-1}$$

Blue n > 1
Red n < 1

2-sigma hint found in **1711.06736**, **1707.09354** from combined Planck+BOSS-DR12 data analysis.

(not statistically significant yet)

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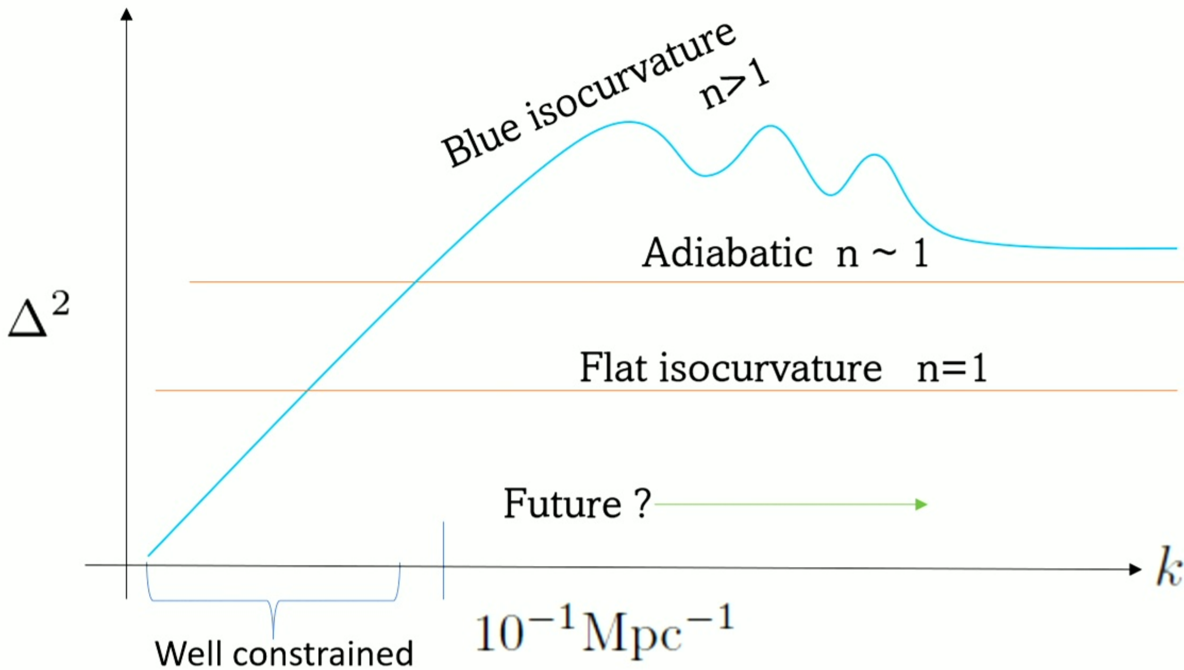

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Other sources of small-scale blue-power ?

A rise in the power on small-scales is generically predicted in several phenomenological models during early-universe:

- PBH isocurvature (induces an almost k^3 spectrum on short scales) [**2012.03698**]
- Phase transition isocurvature (~ k^3) [**2311.16222**]
- Post-inflationary PQ SSB (~ k^3) [**2004.02926**]
- Lumpy DM (~ k^n) [**2306.04674**]

Why study blue isocurvature

- Similar to non-gaussianity and primordial GWs, isocurvature can offer valuable insights into inflation and the presence of spectator fields and their mass scales.

- The theorem in **1509.0585** says that blue isocurvatures with nI > 2.4, uniquely hint towards spectator fields with time-dependent mass during inflation.

- Blue isocurvature can relax the constraint on H-f parametric region $O\left(\frac{H_{\rm inf}}{f_{\rm PQ}\theta_i}\right)$

- The bumps and oscillations in the isocurvature spectrum can acts as signatures complementary to 'cosmological collider' signals.

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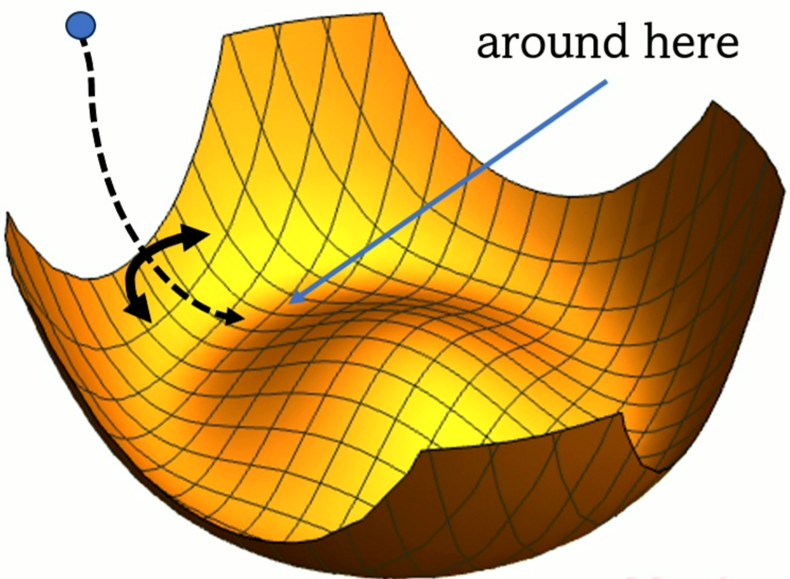
Generate blue-tilted spectra via non-equilibrium radial field

S. Kasuya, M. Kawasaki [0904.3800]

$$\Phi = R e^{i\frac{a}{R}}$$

Field can slosh around here



$$\sqrt{\Delta_a^2} \sim \sqrt{\frac{k^3}{2\pi^2}}\frac{\delta a}{a} \sim \frac{H/2\pi}{R\theta}$$

$$R : O\left(M_{\mathrm{pl}}\right) \rightarrow O\left(f_{\mathrm{PQ}}\right)$$

Massless axion

$$\Box a = 0$$

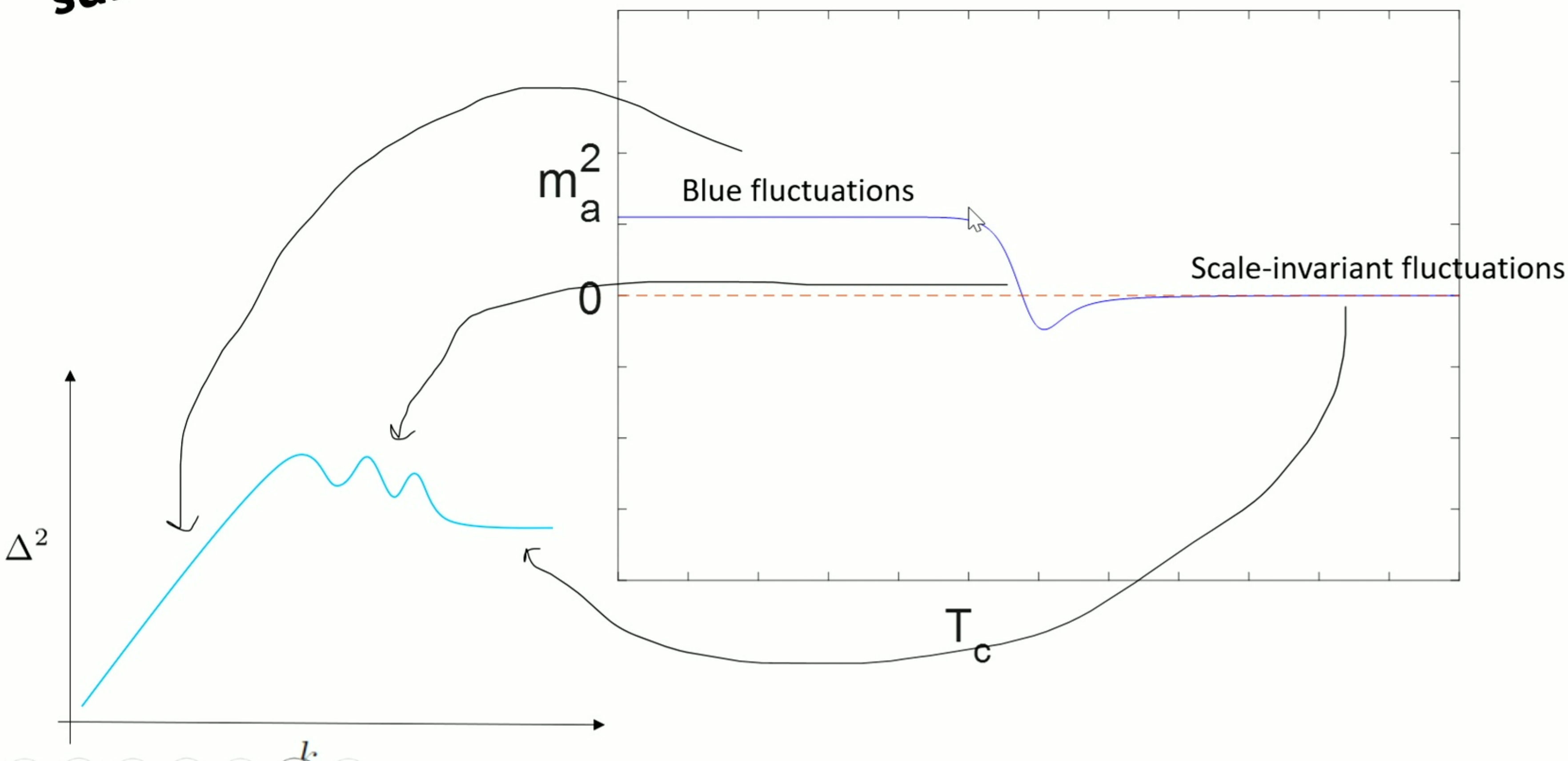
1501.05618 →

Dynamical non-equilb mass

$$\left(\Box - \frac{\Box R}{R}\right) a = 0$$

To summarize...

Time-dependent spectator axion mass



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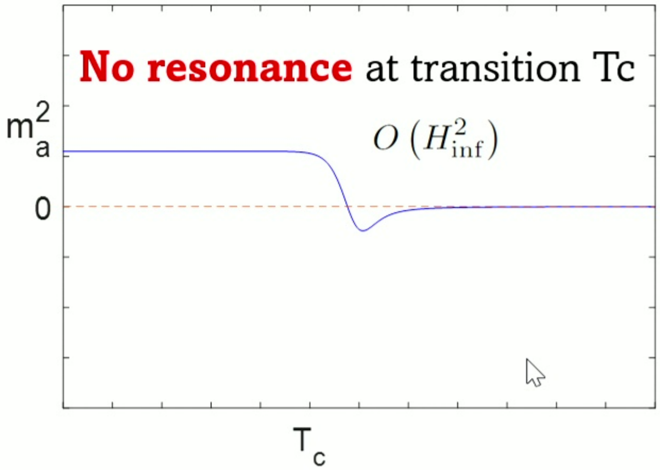
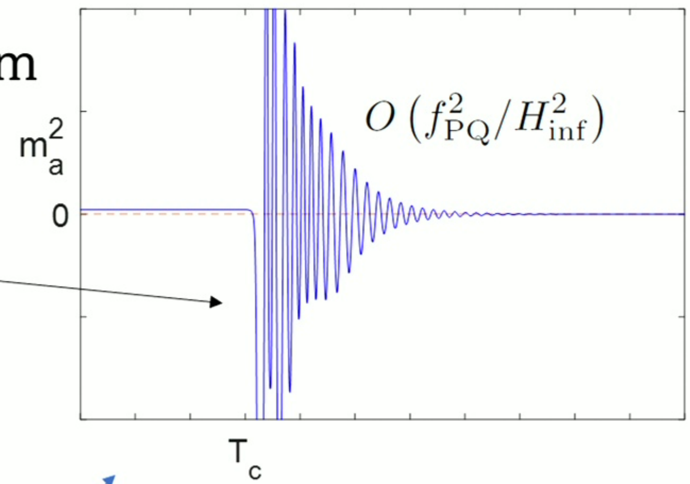
Resonant behavior

Overdamped



Significant deviation from flat-direction results in **resonant behavior** at transition Tc

Underdamped



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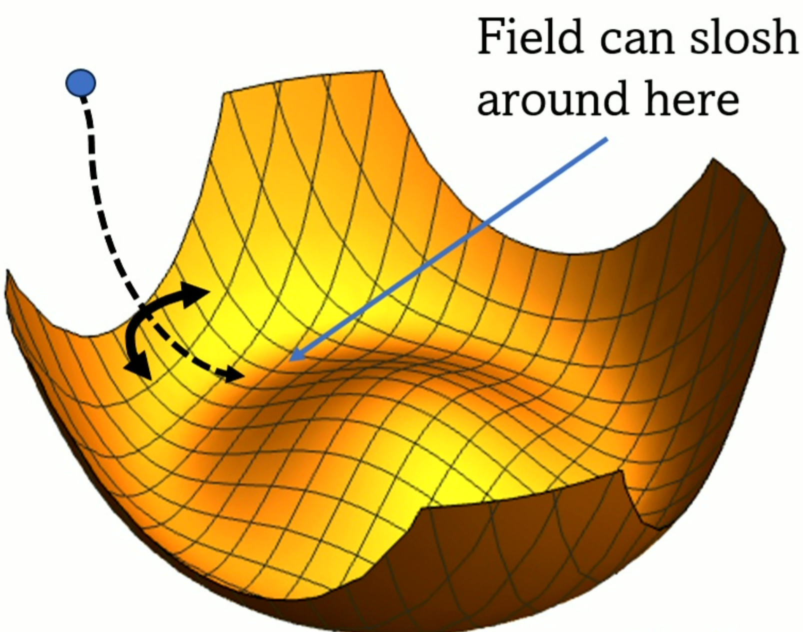

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$$R : O\left(M_{\rm pl}\right) \to O\left(f_{\rm PQ}\right)$$

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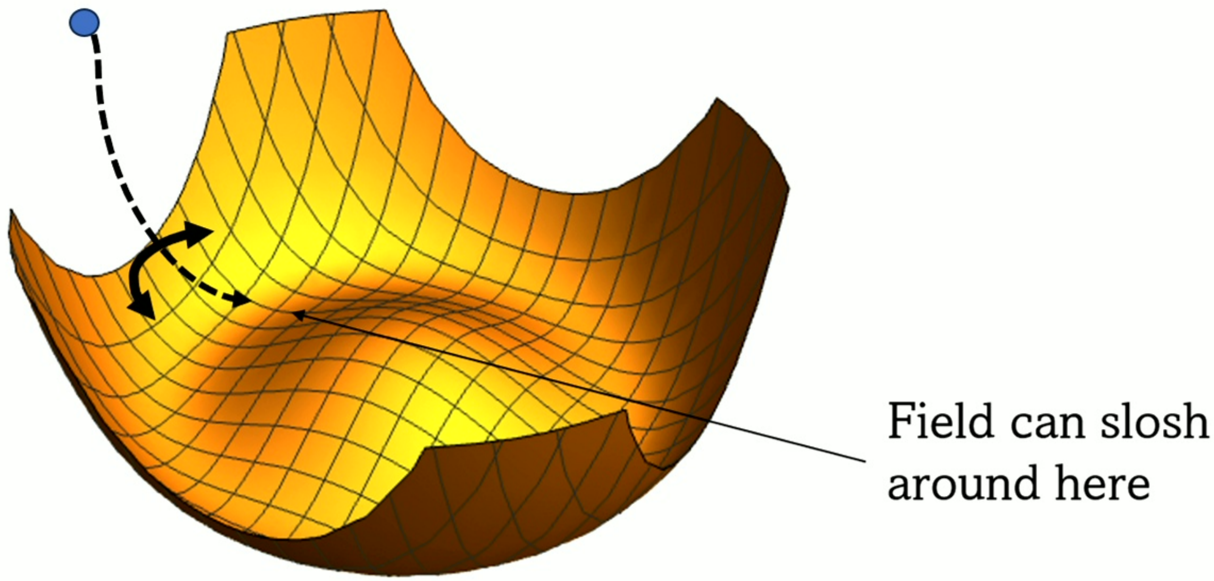
Field can slosh
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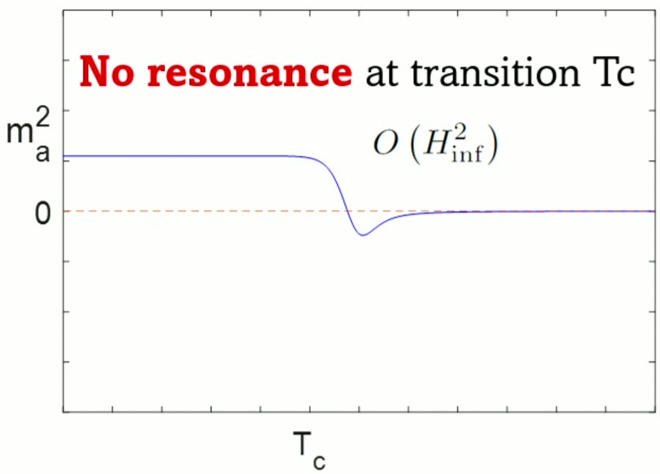
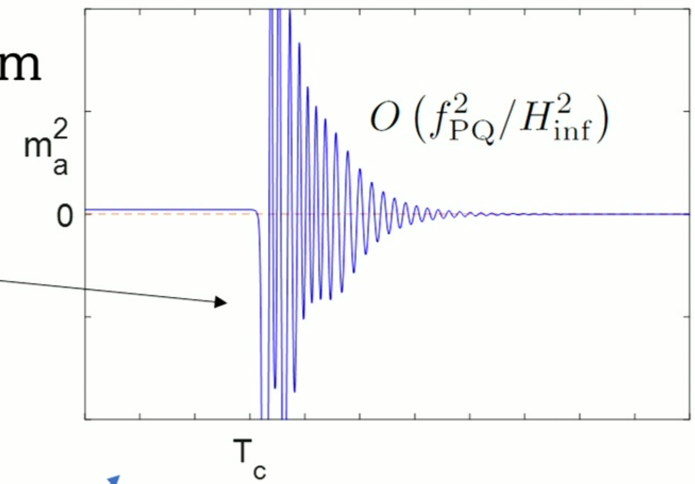


Significant deviation from flat-direction results in **resonant behavior** at transition Tc

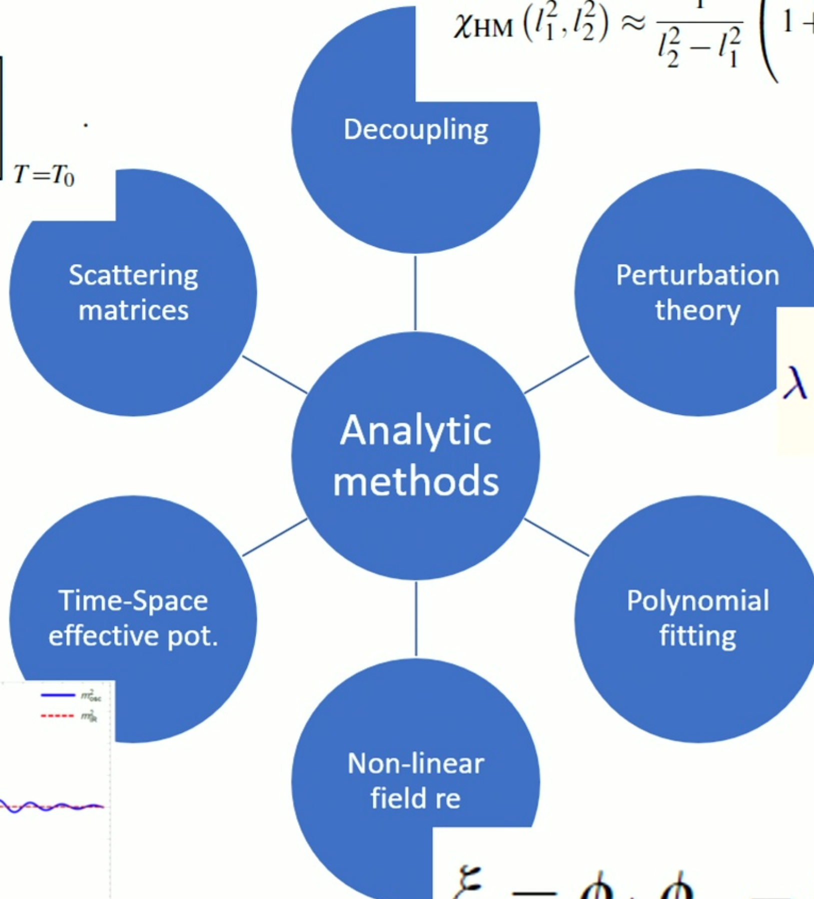
Underdamped



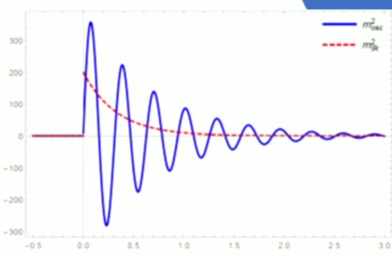
$$\Box a = 0 \quad \longrightarrow \quad \left(\Box - \frac{\Box R}{R}\right) a = 0$$

$$\chi_{\mathrm{HM}}\left(l_1^2, l_2^2\right) \approx \frac{1}{l_2^2 - l_1^2}\left(1 + 2\sqrt{-l_1^2} + \frac{8/3}{\sqrt{-l_1^2}}\left(-1 + e^{-\sqrt{-l_1^2}}\cos\left[l_2\right]\right)\right)$$

$$\begin{bmatrix} y_1 \\ \dot{y}_1 \end{bmatrix}_{T_N^-} = \prod_{j=0}^{N-1} S(T_j, T_{j+1}) \begin{bmatrix} y_1 \\ \dot{y}_1 \end{bmatrix}_{T=T_0}.$$



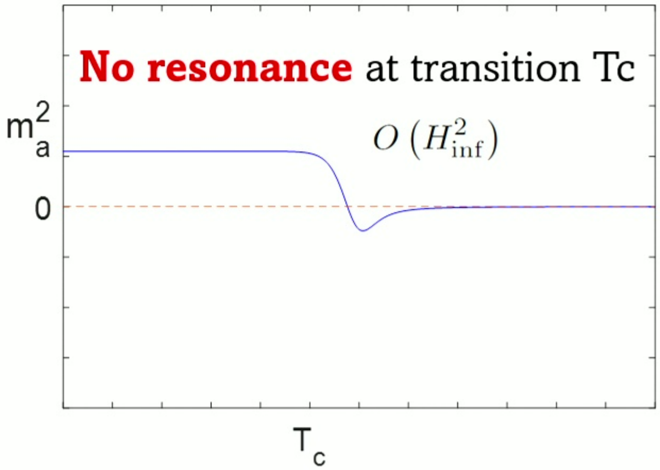
$$\lambda \leftrightarrow O\left(\sqrt{\frac{\phi_-}{\phi_+}}\right)$$



$$\xi = \phi_+\phi_- - F^2$$

Resonant behavior

Overdamped



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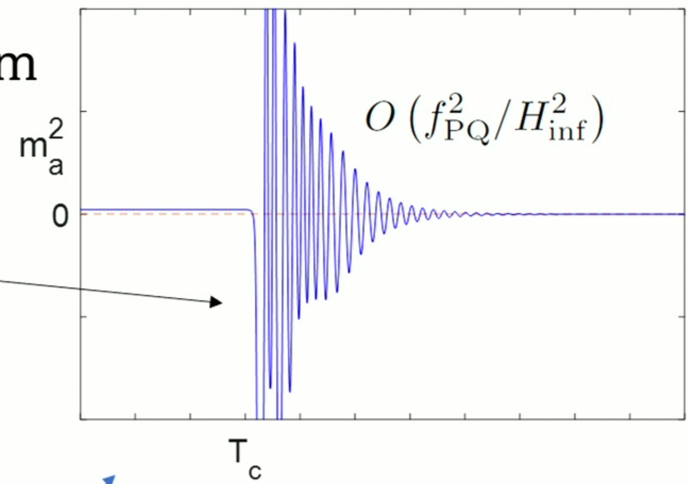

Significant deviation from flat-direction results in **resonant behavior** at transition Tc

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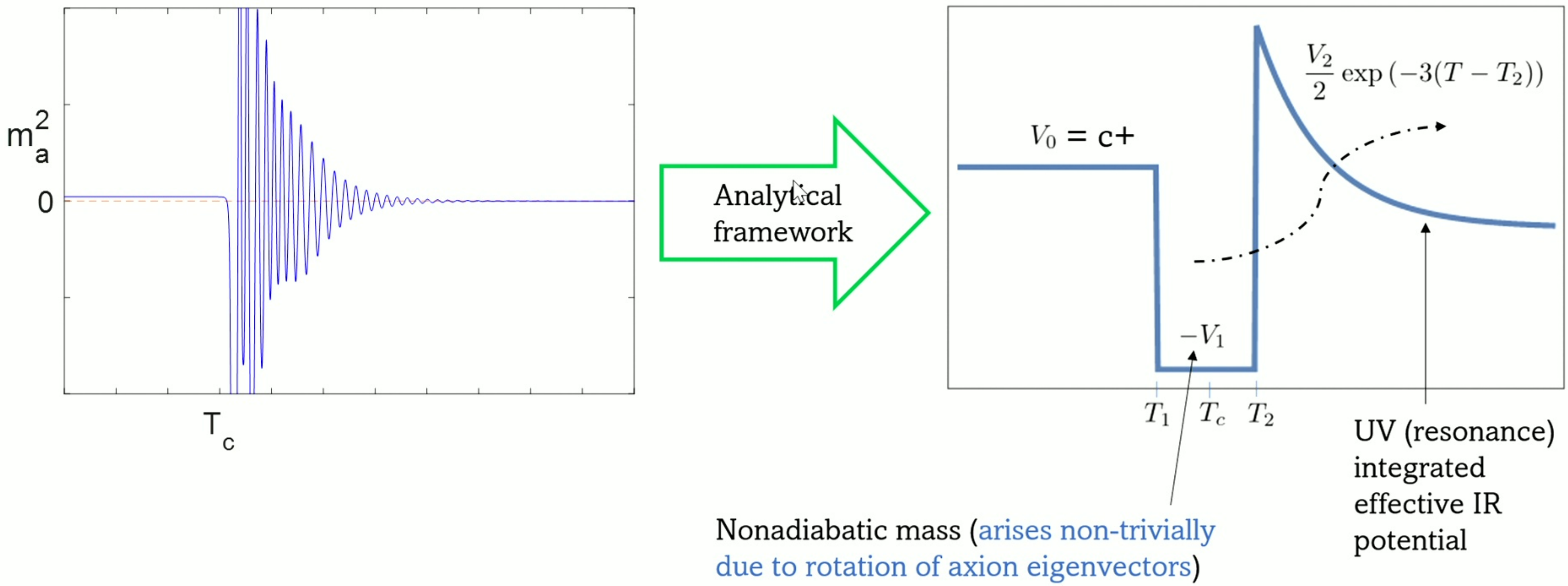
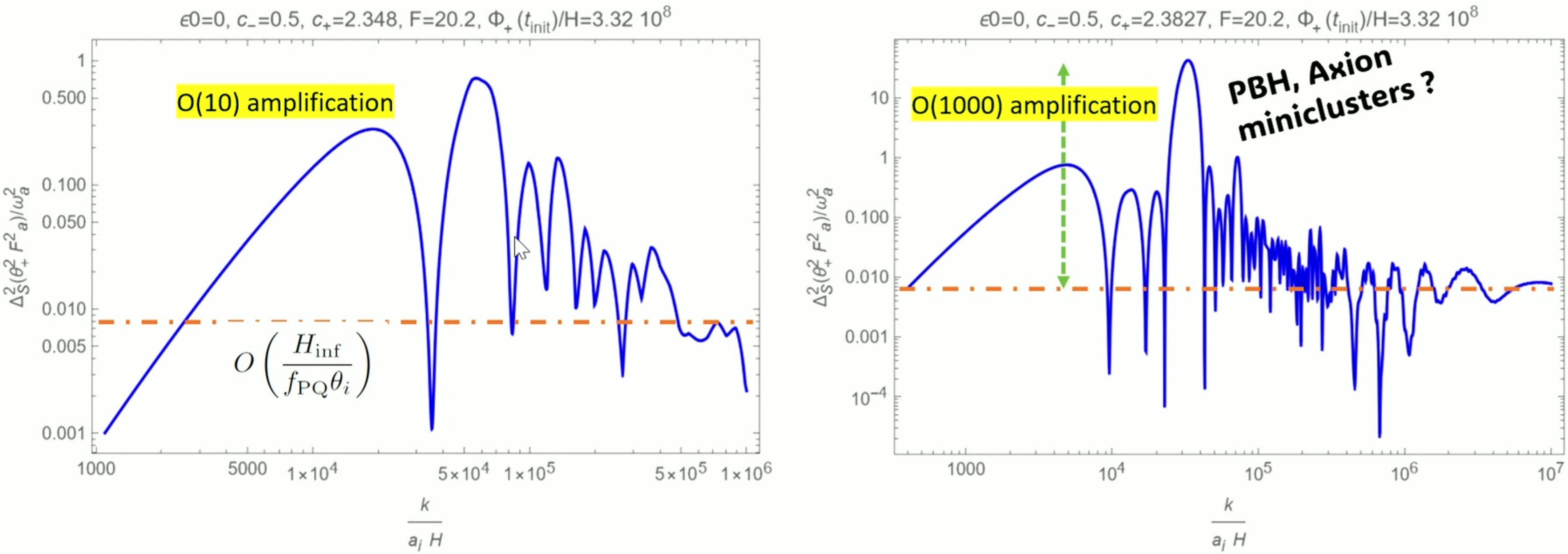
Key physics: Scattering of tachyonic quantum modes as they exit the well



The tachyonic mass results in mode amplification and quantum modes grow

Axionic large blue isocurvature spectra for underdamped scenario

1. Large amplification ~O(10-1000) due to the tachyonic dip,
2. and multiple bumps due to quantum scattering of vacuum modes



2110.02272 (Chung and Sai)

SUSY axion model

S. Kasuya, M. Kawasaki [0904.3800]

Renormalizable superpotential: $W_{\rm PQ} = h\left(\Phi_+\Phi_- - F_a^2\right)\Phi_0$

subscripts on Φ indicate U(1) PQ charges.

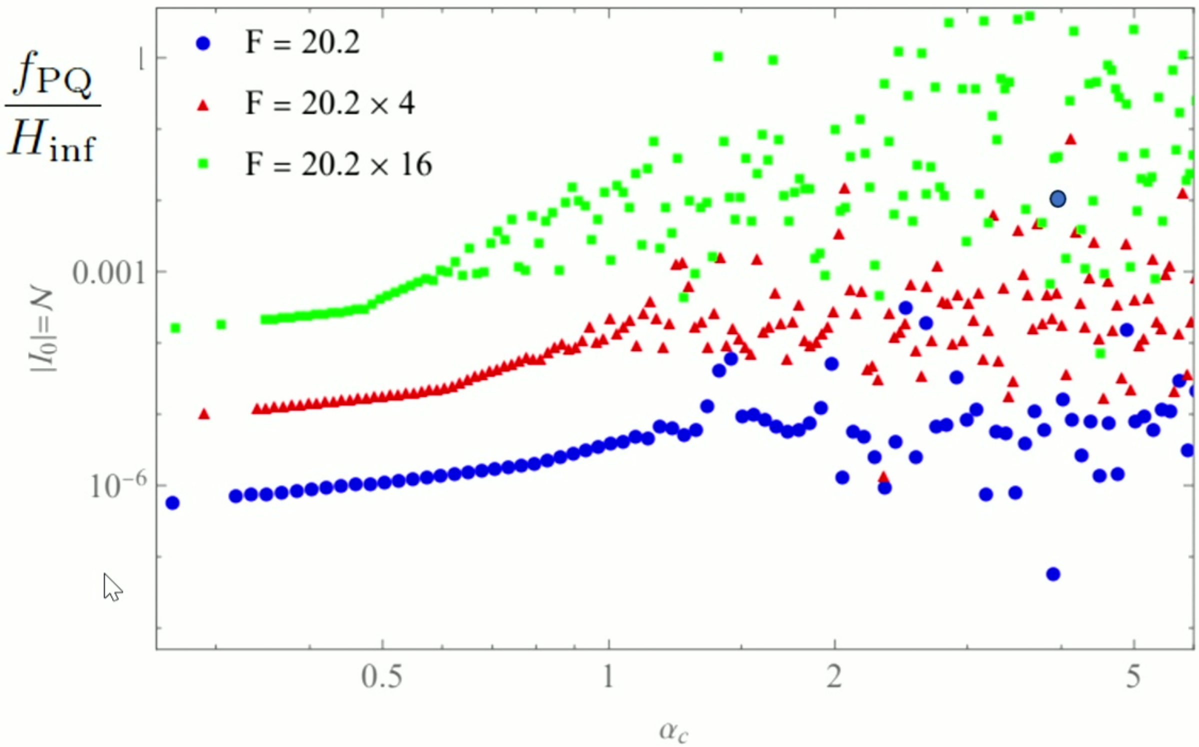
$$\Phi_+\Phi_- - F_a^2 = 0 \qquad \Phi_0 = 0 \qquad \text{flat-direction}$$

$$V = \frac{1}{2}c_+H^2\left|\Phi_+\right|^2 + \frac{1}{2}c_-H^2\left|\Phi_-\right|^2 + \frac{1}{2}\left|\Phi_+\Phi_- - F_a^2\right|^2$$

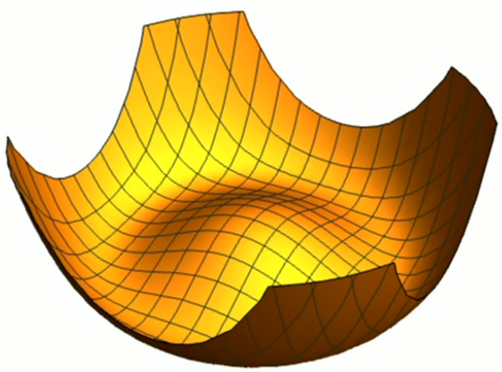
Kaehler induced mass terms F-term

Large kinetic energy results in chaos…

$$F = \frac{f_{PQ}}{H_{\rm inf}}$$

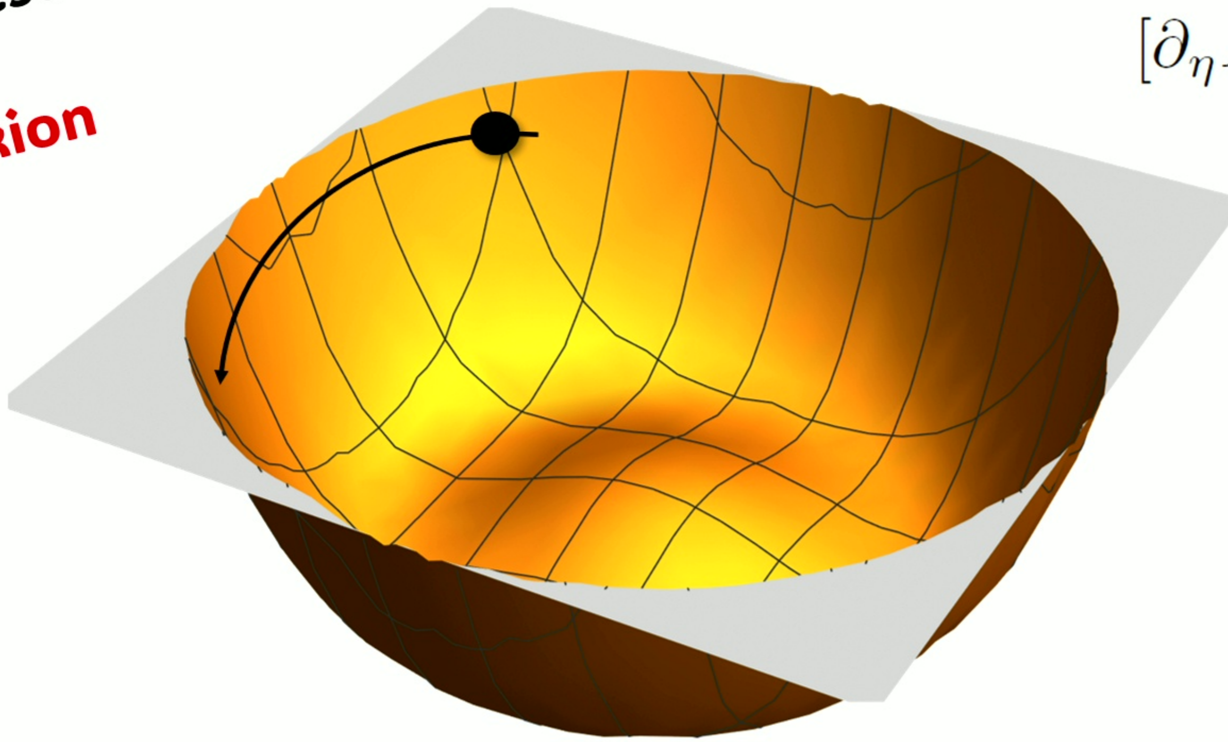


(Chung and Sai 2309.17010)



…leads to interesting features.

Other interesting dynamics: rotating axion



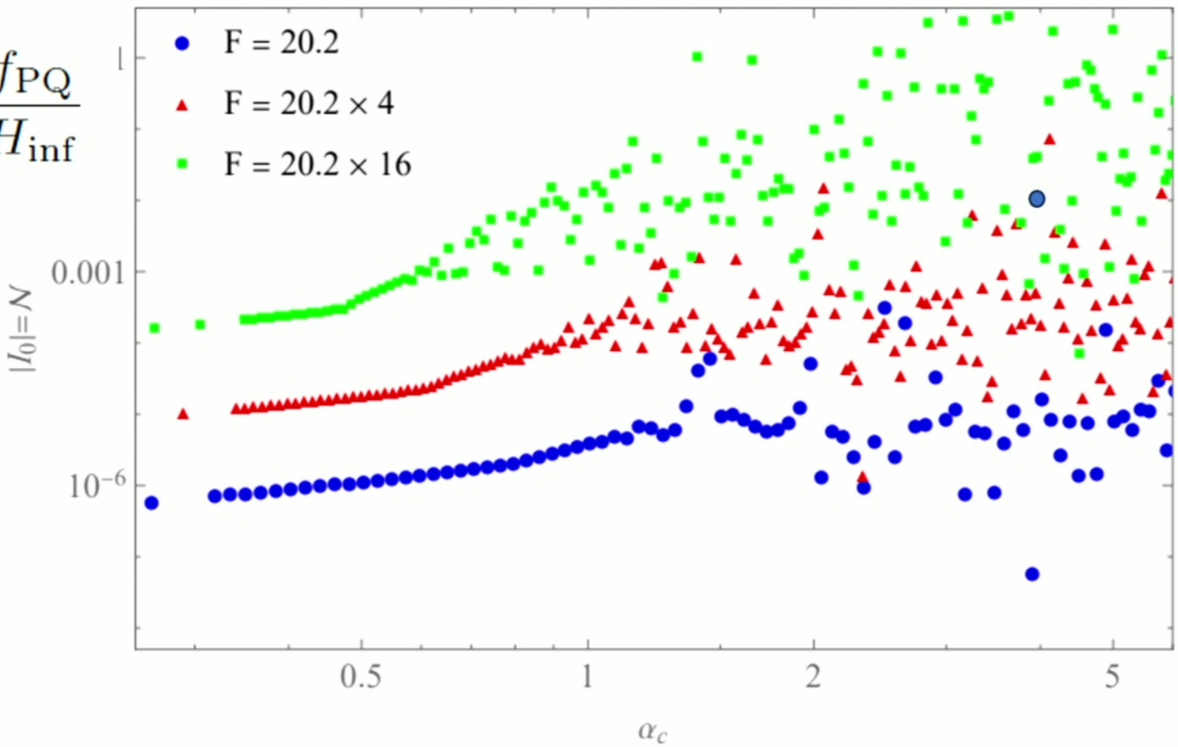
$$[\partial_\eta R, \partial_\eta a] \neq 0$$

Generates blue isocurvature spectrum

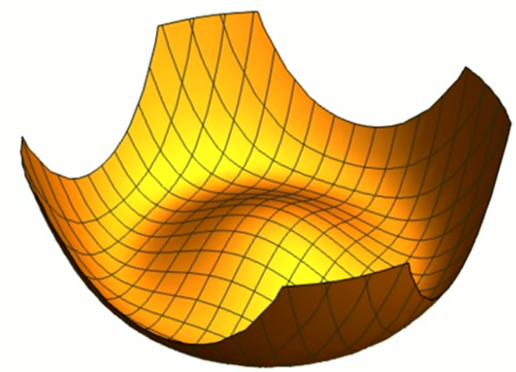
[in preparation]

Large kinetic energy results in chaos…

$$F = \frac{f_{\rm PQ}}{H_{\rm inf}}$$



(Chung and Sai 2309.17010)



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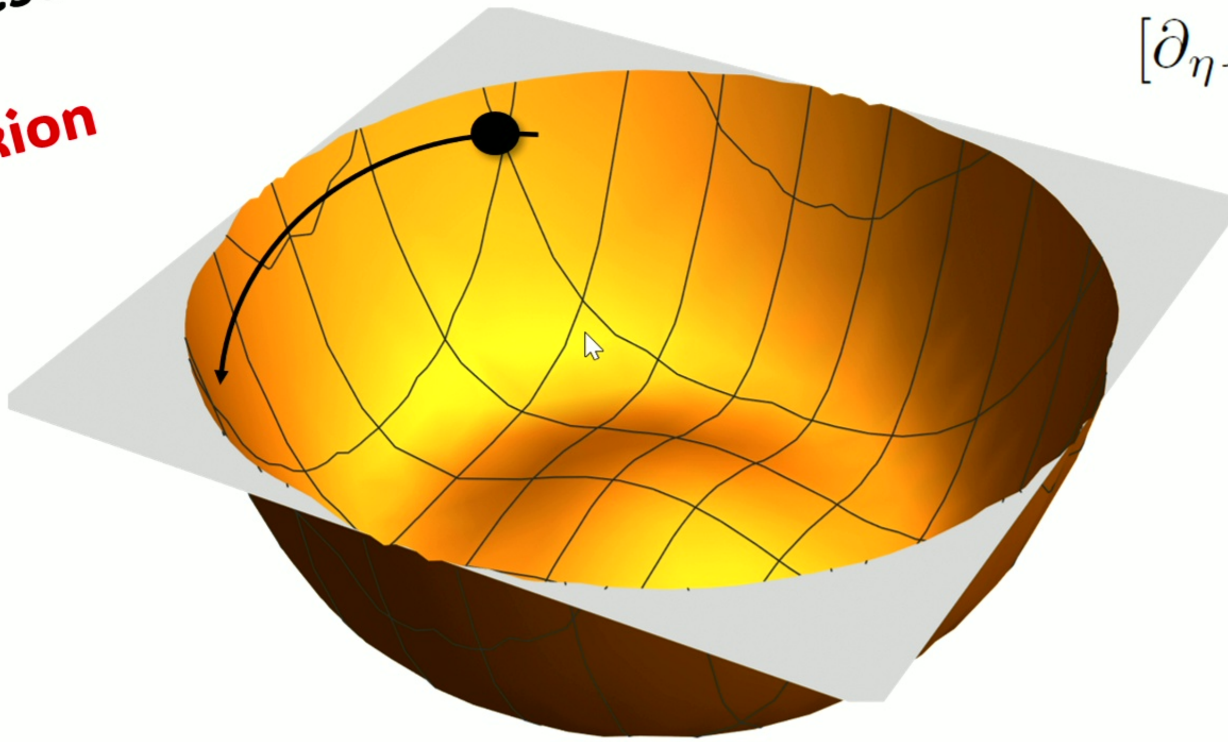


Generates blue isocurvature spectrum

[in preparation]

Blue isocurvature may be discoverable in the future

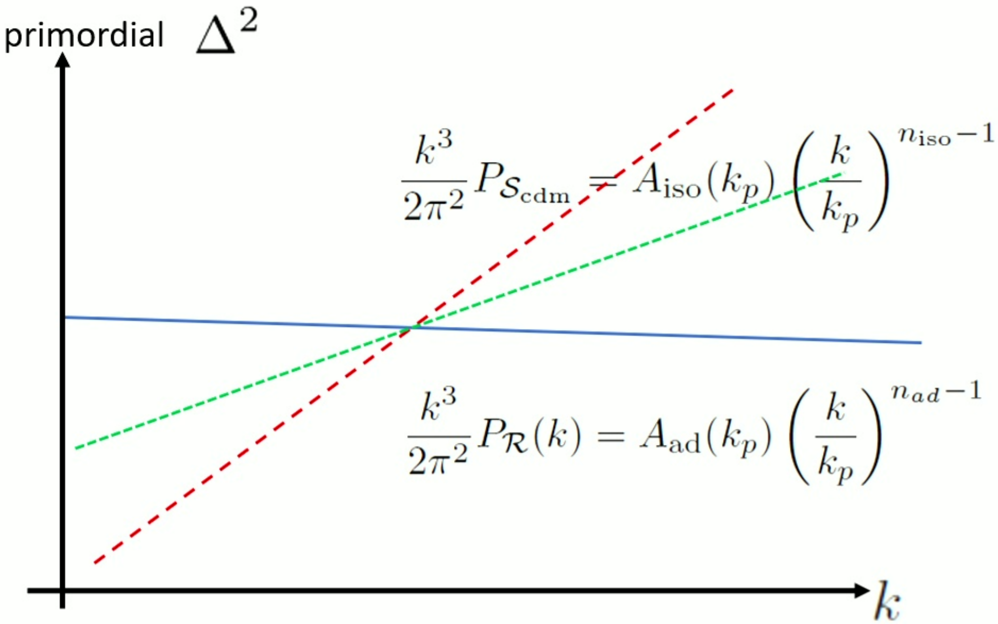
How much sensitivity is there for discovery in future data?

We will try to answer this in the context of couple of experiments like Euclid and MegaMapper

We will use Fisher forecasting technique and employ EFTofLSS as the underlying theory

Main advantages of using EFTofLSS:

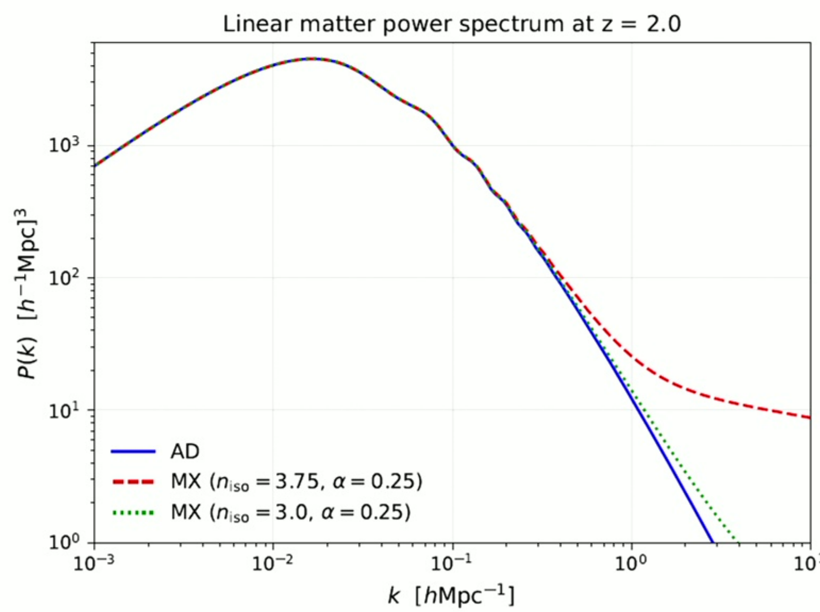
1) Systematics are well understood
2) Easy to adapt to isocurvature



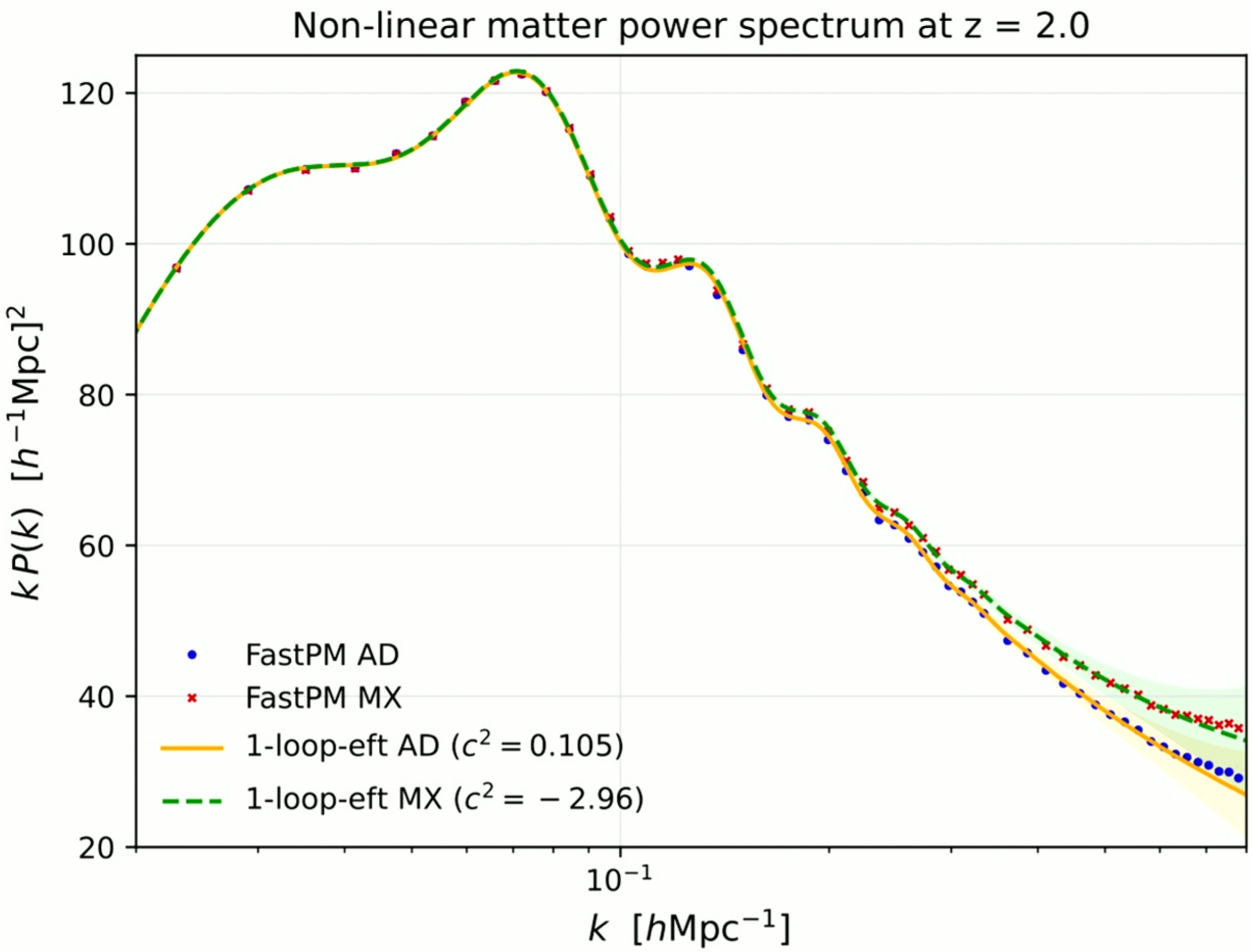
$$\frac{k^3}{2\pi^2} P_{\mathcal{S}_{\rm cdm}} = A_{\rm iso}(k_p) \left(\frac{k}{k_p}\right)^{n_{\rm iso}-1}$$

$$\frac{k^3}{2\pi^2} P_{\mathcal{R}}(k) = A_{\rm ad}(k_p) \left(\frac{k}{k_p}\right)^{n_{ad}-1}$$

$$P_{\rm lin}^{\rm MIXED}(k, z \gg z_{\rm eq}) = P_{\rm lin}^{\rm AD}(k, z) + P_{\rm lin}^{\rm ISO}(k, z)$$



Main parameter that will be constrained $\alpha = \frac{A_{\rm iso}(k_{\rm p})}{A_{\rm ad}(k_{\rm p})}$


Non-linear matter power spectrum at z = 2.0
120
100
80
60
40
20
$k\,P(k)$ $[h^{-1}\mathrm{Mpc}]^2$
10^{-1}
k $[h\mathrm{Mpc}^{-1}]$
FastPM AD
FastPM MX
1-loop-eft AD ($c^2 = 0.105$)
1-loop-eft MX ($c^2 = -2.96$)

Standard Perturbation Theory (SPT)

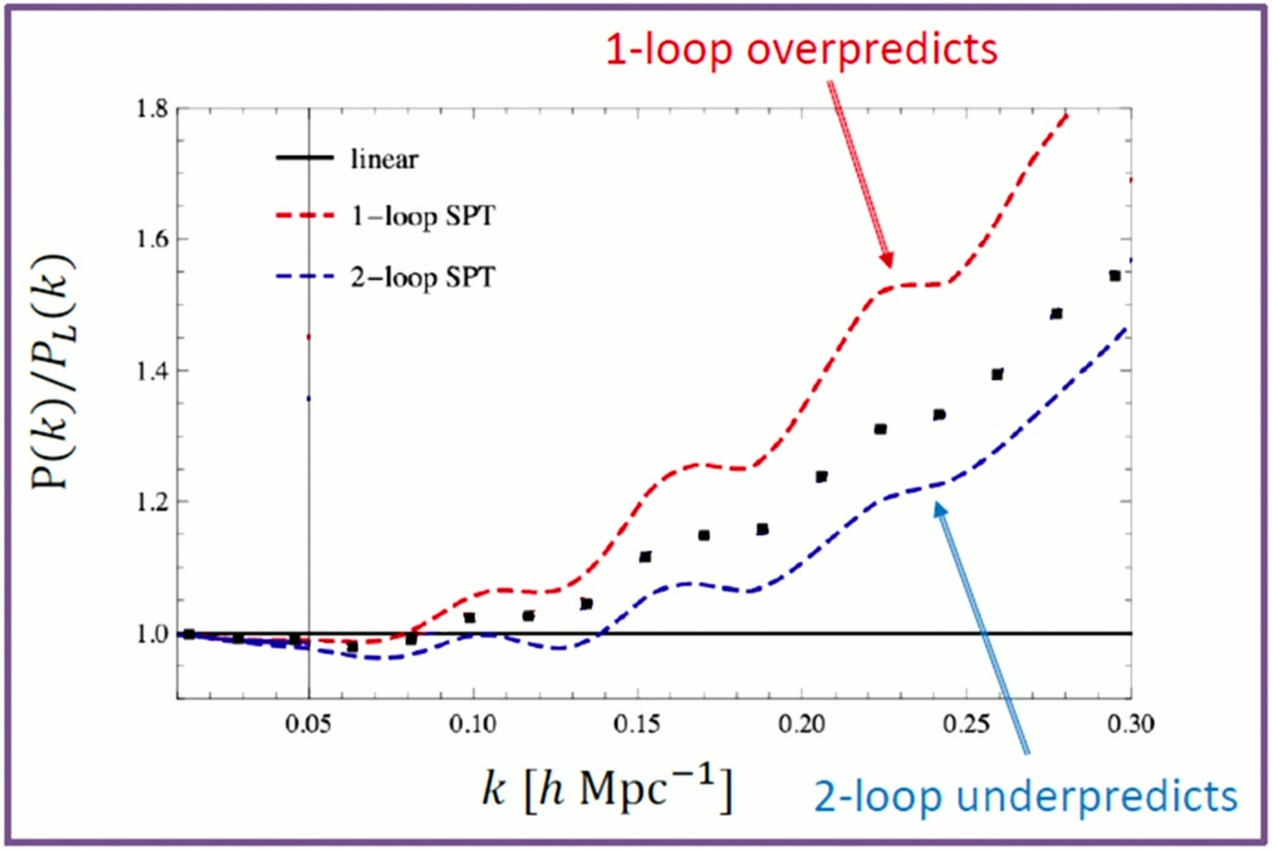
- SPT treats matter as a pressureless and collisionless cold Newtonian fluid.

$\dot{\delta} + \nabla \cdot [(1+\delta)\boldsymbol{v}] = 0,$	Continuity Equation
$\dot{\boldsymbol{v}} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\mathcal{H}\boldsymbol{v} - \nabla\phi,$	Euler Equation
$\nabla^2\phi = 4\pi G a^2 \bar{\rho}\delta,$	Poisson Equation

$$\theta = \nabla \cdot v$$

$$\delta(\mathbf{k},\tau) = D(\tau)\delta^{(1)}(\mathbf{k}) + D^2(\tau)\delta^{(2)}(\mathbf{k}) + D^3(\tau)\delta^{(3)}(\mathbf{k}) + \ldots$$

$$\theta(\mathbf{k},\tau) = -\mathcal{H}(\tau)f(\tau)\left[D(\tau)\theta^{(1)}(\mathbf{k}) + D^2(\tau)\theta^{(2)}(\mathbf{k}) + D^3(\tau)\theta^{(3)}(\mathbf{k}) + \ldots\right]$$



Baldauf, Adv. Cosm.

Adding more loops in SPT doesn't lead to a smooth convergence

How to obtain an EFT of matter fluid ?

$$\mathcal{O}_l(\vec{x},t) = [\mathcal{O}]_\Lambda(\vec{x},t) = \int d^3x'\, W_\Lambda(\vec{x}-\vec{x}')\mathcal{O}(\vec{x}') \ .$$

$$\begin{aligned} \dot{\delta}_\Lambda + \nabla \cdot [(1+\delta_\Lambda \mathbf{v}_\Lambda] &= 0 \\ \dot{\mathbf{v}}_\Lambda + (\mathbf{v}_\Lambda \cdot \nabla)\, \mathbf{v}_\Lambda &= -\mathcal{H}\mathbf{v}_\Lambda - \nabla\phi_\Lambda - \frac{1}{\rho_\Lambda}\nabla\underline{\underline{\tau}} \end{aligned}$$

Baumann+12
Carrasco+12

effective **stress-tensor**

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Baumann+12
Carrasco+12

effective **stress-tensor**

$$\delta(\boldsymbol{k},\tau) = \delta^{(1)}(\boldsymbol{k},\tau) + \delta^{(2)}(\boldsymbol{k},\tau) + \delta^{(3)}(\boldsymbol{k},\tau)$$

$$P_{\rm NL}(k,z) = P_{11}(k,z,\Lambda) + P_{22}(k,z,\Lambda) + 2P_{13}(k,z,\Lambda)$$

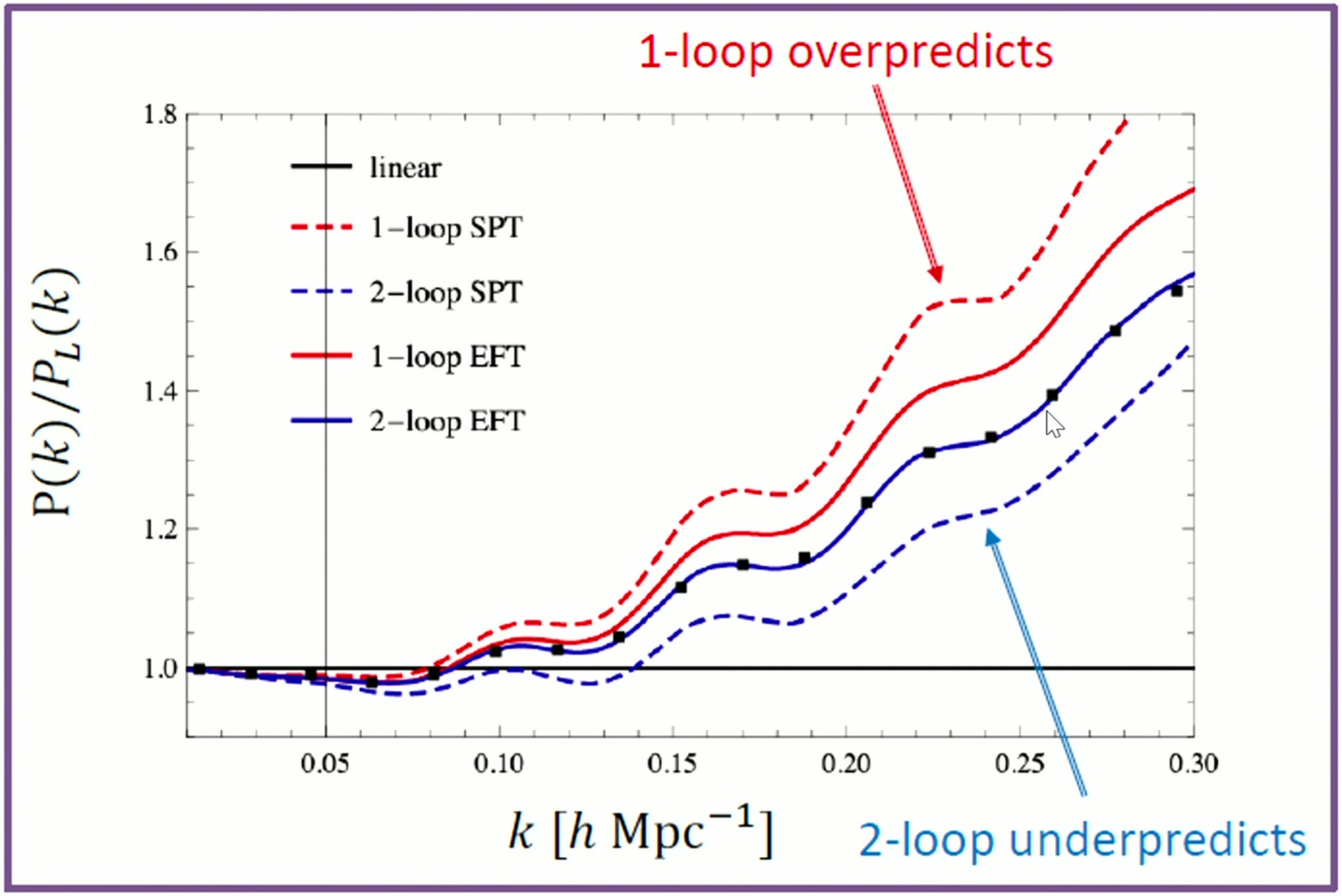
*assuming Gaussian fields

$$\delta(\boldsymbol{k},\tau) = \delta^{(1)}(\boldsymbol{k},\tau) + \delta^{(2)}(\boldsymbol{k},\tau) + \delta^{(3)}(\boldsymbol{k},\tau) - k^2 c_{\rm s}^2(\tau)\delta^{(1)}(\boldsymbol{k},\tau) + \dots$$

The new term induced from <u>small-scale</u> physics

$$P_{\rm NL}(k,z) = P_{11}(k,z,\Lambda) + P_{22}(k,z,\Lambda) + 2P_{13}(k,z,\Lambda) - 2c_s^2(z,\Lambda)k^2 P_{11}(k,z,\Lambda)$$

1 –loop counterterm



Baldauf, Adv. Cosm.

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The new term induced from <u>small-scale</u> physics

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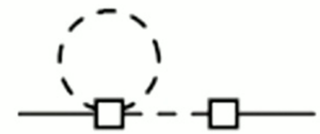
1 –loop counterterm

Renormalization of PT

On very large scales,

$$\lim_{k\to 0} P_{13}(k) \approx -k^2 P_{11}(k) \left(\frac{61}{630\pi^2} \int^{\Lambda} dq P_{11}(q) \right)$$



The cutoff dependence is absorbed by the counterterm!

$$P_{\text{1-loop}}(k,z) = P_{11}(k,z) + P_{22}(k,z) + \boxed{\left(P_{13}(k,z,\Lambda) - 2c_{\Lambda}^2(z) k^2 P_{11}(k,z)\right)} - 2c_{\text{ren}}^2(z) k^2 P_{11}(k,z)$$

renormalized fluid parameter

$$c_s^2 = c_{\Lambda}^2 + c_{\text{ren}}^2$$

Forecast

The **Euclid** satellite (launched on 1 July 2023) will measure star-forming luminous galaxies containing Hα emitters using a near-infrared telescope [**1910.09273**], reaching out to a redshift of **z ~ 2**

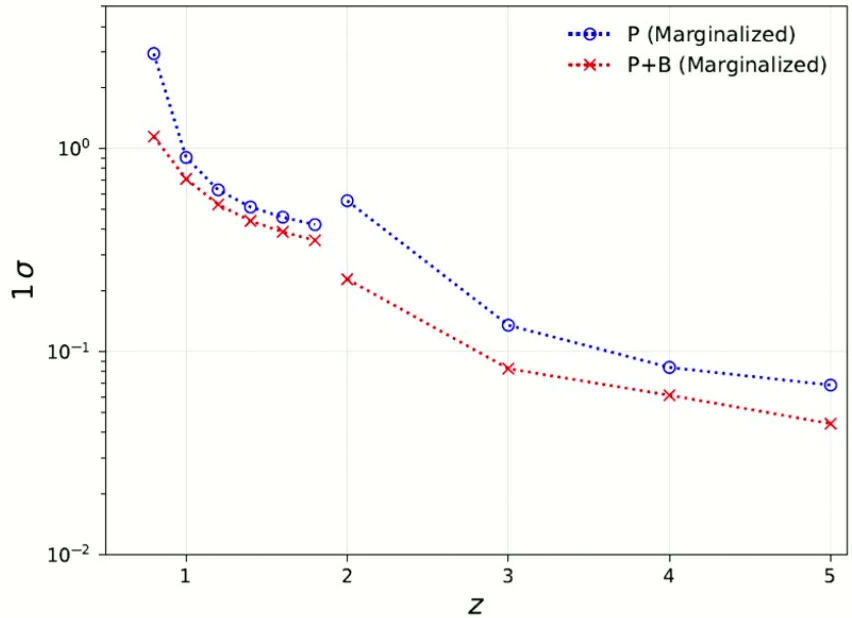
MegaMapper (MM) [ground-based, 2030?] will survey galaxies at high-redshift **2<z<5** primarily looking for Lyman Break Galaxies (LBGs) [**1907.11171**].

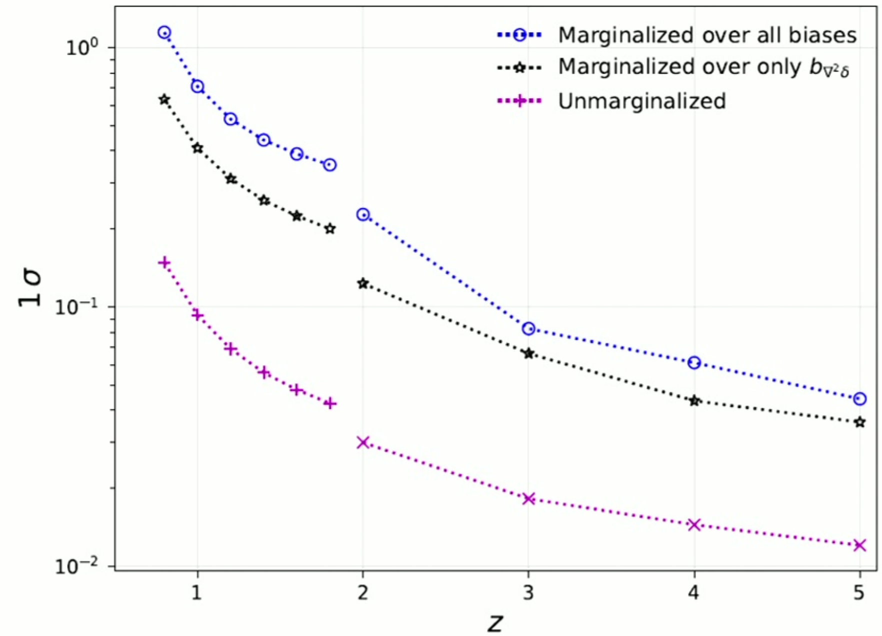
$$
\begin{aligned}
A &= 1 \\
\Omega_b &= 0.0486, \\
\Omega_c &= 0.2589, \\
n_s &= 0.9667, \\
h &= 0.6774
\end{aligned}
$$

$$\{\text{nuisance}\} = \{b_1, b_2, b_{\mathcal{G}_2}, b_{\Gamma_3}, b_{\nabla^2\delta}, b_\epsilon, b_{\nabla^2\epsilon}\}$$

$$A = A_\mathrm{s}/A_\mathrm{s,fid} \text{ for } A_\mathrm{s,fid} = 2.1413 \times 10^{-9}$$

1 sigma error forecast on the ratio of the amplitude of blue isocurvature compared to adiabatic





1) Most of the degradation in sensitivity comes from the Laplacian $b_{\nabla^2\delta}$

$$P_{gg,\nabla^2\delta}(k) = -2b_1 b_{\nabla^2\delta}\left(\frac{k}{k_*}\right)^2 P_{11}(k)$$

$$b_1 = \sqrt{1+z}$$

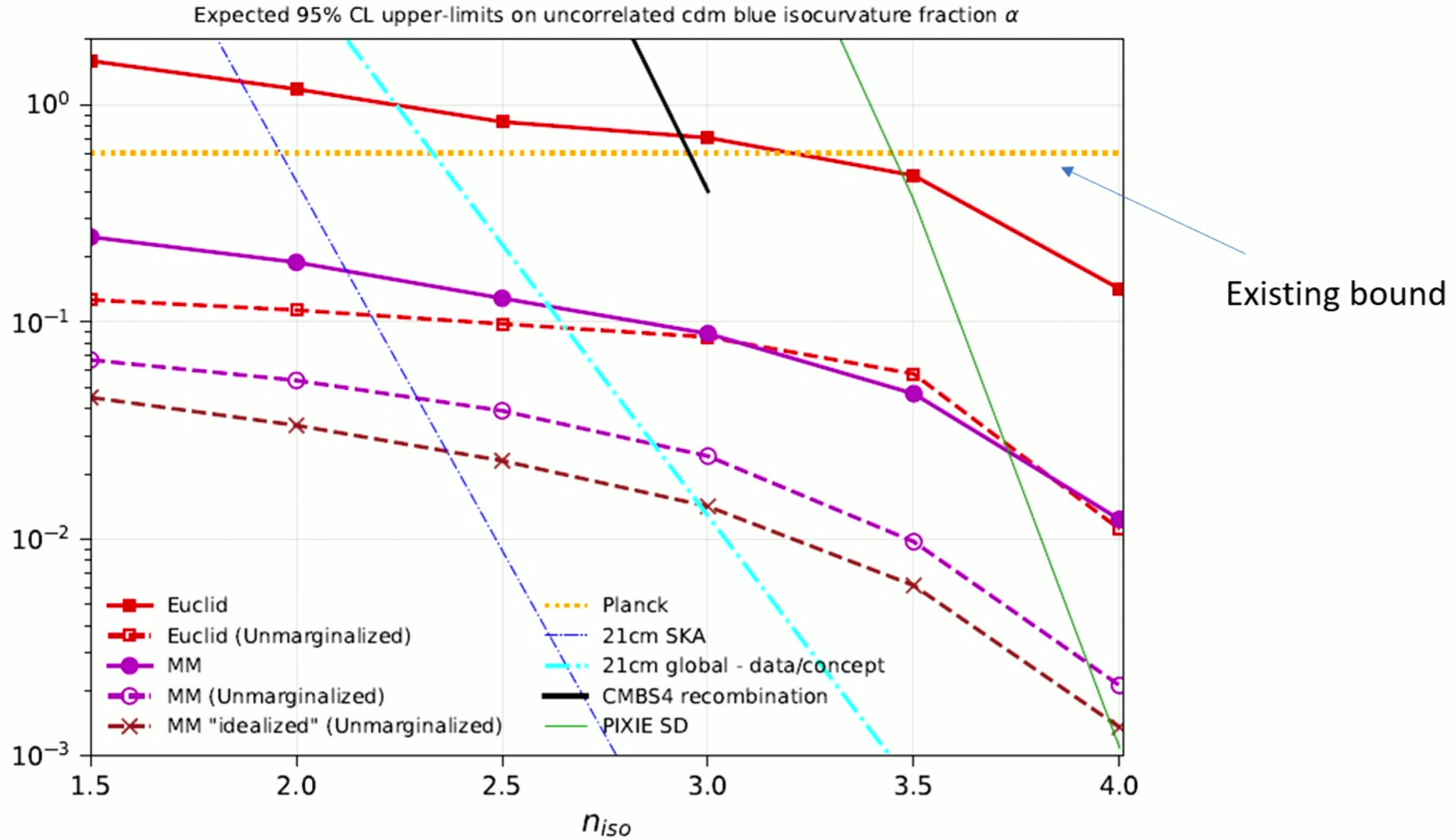
$$k_* \approx k_{\mathrm{HD}} \approx 0.4\,(D_+(z)/D_+(0))^{-4/3}\,(\mathrm{h/Mpc})$$

A leading isocurvature term:

$$P_{gg} \supset b_1^2 P_{11}^{\mathrm{AD}}(k)\alpha\left(\frac{f_c}{3}\right)^2\left(\frac{T_{\mathrm{iso}}(k)}{T_{\mathrm{ad}}(k)}\right)^2\left(\frac{k}{k_{\mathrm{p}}}\right)^{n_{\mathrm{iso}}-n_{\mathrm{ad}}}$$

$$\propto b_1^2\alpha P_{11}^{\mathrm{AD}}(k)\left(\frac{k}{k_{\mathrm{p}}}\right)^{n_{\mathrm{iso}}-n_{\mathrm{ad}}-0.5}$$

With MM there is a strong possibility of a 5-sigma detection of high-blue isocurvature



- Euclid can give a factor of few improvement for the high spectral index case
- MM can improve the $\alpha = \frac{A_{\rm iso}(k_{\rm p})}{A_{\rm ad}(k_{\rm p})}$ constraint by 1 to 1.5 orders of magnitude.

Extensions

- Improvements:
  - Include redshift space distortion effects,
  - Apply a realistic cutoff (break) in the power spectrum.

- Degeneracy with neutrinos. Explore neutrino mass constraint in presence of blue isocurvature. Similar effects for ULAs and thereby one can relax current ULA-DM constraints.

- Redshift variation of counter-term can give non-trivial information about the small-scale power.

- A significant small-scale power can also emerge from other sources such as lumpy DM, PBH, certain inflationary models etc. It will be interesting to assess possible degeneracy breaking signatures such as associated NG (magnitude and shape profile) to help differentiate these signals.