Alternatives to Inflation as Cosmological Particle Scanners

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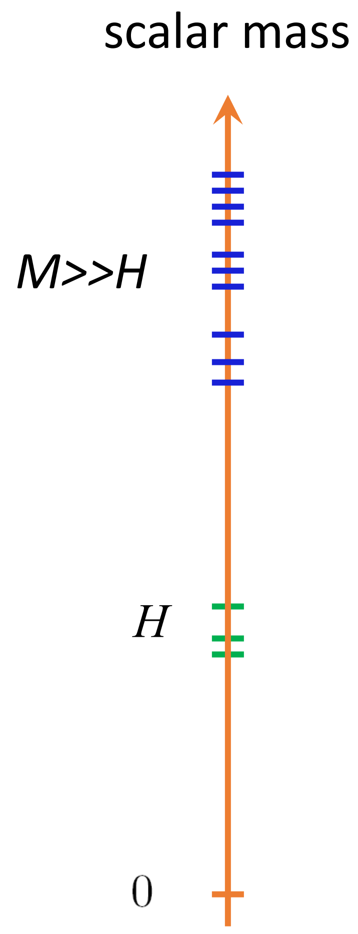
Quasi-Single Field Inflation and Cosmological Collider Physics



spectrum of realistic single field inflation models

- To get *m* << *H*, tuning is necessary generically

$$m^2 \sim H^2 \xrightarrow{\text{tune}} m^2 \lesssim \mathcal{O}(0.01) H^2$$ The η - problem

- Many others remain of order *H* or higher

- These fields are not important classically,
  but may be important quantum mechanically

What are the observational signatures for all the particles present during **INFLATION**?

The particle mass and spin spectra are encoded in various soft limits of non-Gaussianities:

E.g. **Squeezed limit bispectrum**

$$S \xrightarrow[\text{limit}]{\text{squeezed}} \underbrace{e^{-\pi\mu}}_{\text{Boltzmann suppression}} \left(\frac{k_{\text{long}}}{k_{\text{short}}}\right)^{\overbrace{\frac{1}{2}\pm i\mu}^{\text{mass}}} \underbrace{P_s}_{\text{spin}}(\cos\theta)$$

Boltzmann suppression

mass spin

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

(XC, Wang, 09; Baumann, Green, 11; Noumi, Yamaguchi, Yokoyama, 12)
(Arkani-Hamed, Maldacena, 15; Lee, Baumann, Pimentel, 16; XC, Wang, Xianyu, 16,18)
(An, McAneny, Ridgway, Wise, 17; Kumar, Sundrum, 17,18)
… … …

Applications and Extensions

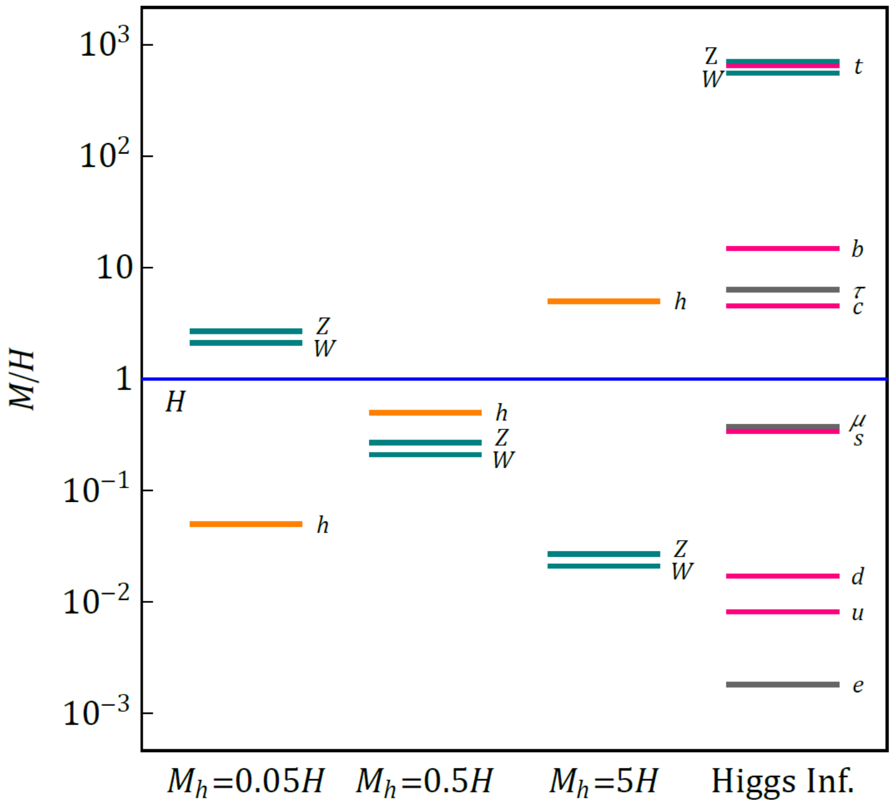
- Standard Model spectrum in inflationary background

Case without symmetry breaking

(XC, Wang, Xianyu, 16, 17)

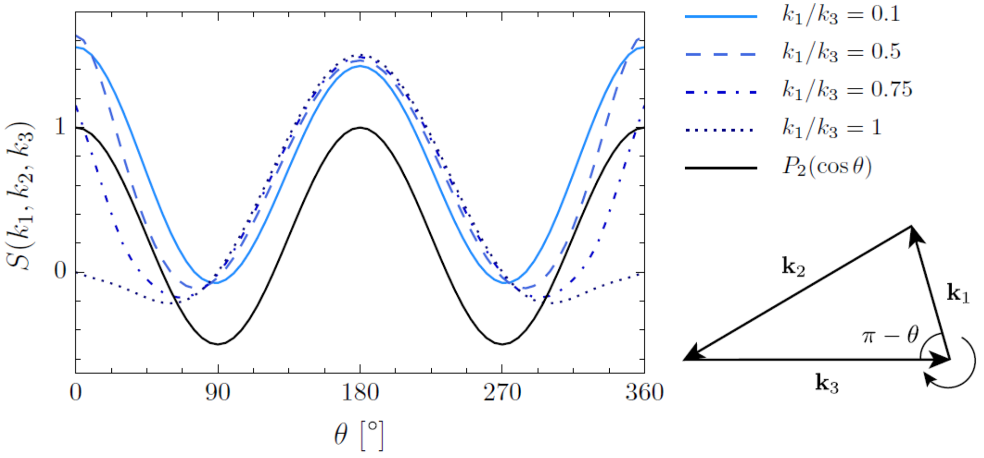
Case with symmetry breaking – larger signals in non-G

(Kumar, Sundrum, 17)



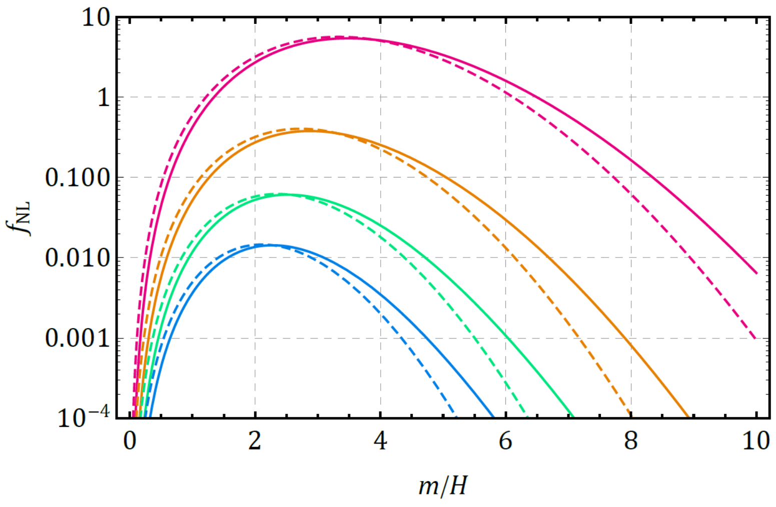
- Signature of higher spin fields

(Arkani-Hamed, Maldacena, 15;
Lee, Baumann, Pimentel, 16;
Arkani-Hamed, Baumann, Lee, Pimentel, 18)



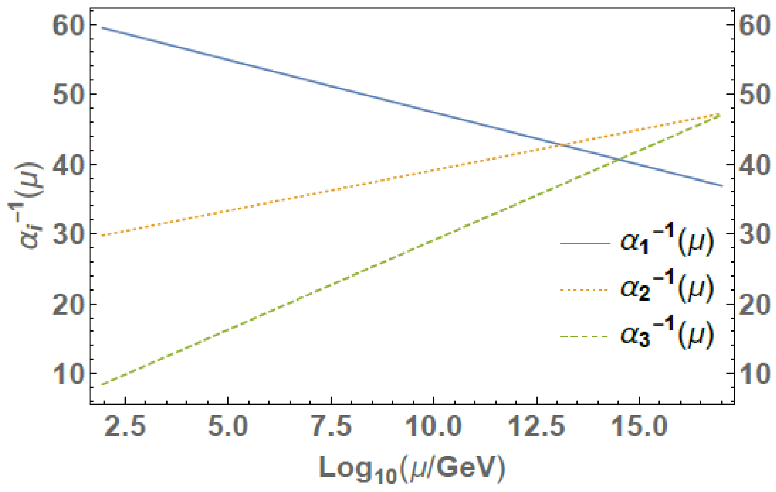
- Signature of sterile neutrino and gauge bosons

(XC, Wang, Xianyu, 18)
(Wang, Xianyu, 20)



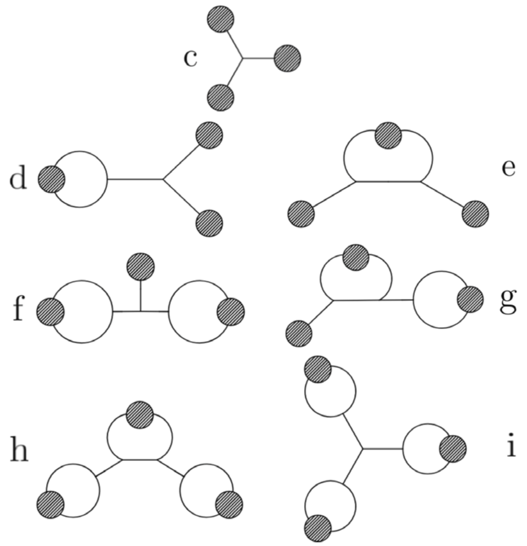
- Signatures of Higher dimensional Grand Unification Theory;
  Curvaton scenarios

  (Kumar, Sundrum, 18, 19)
  (Lu, Wang, Xianyu, 19)



- QSFI in strong coupling;
  Enhancement of galactic halo correlations

  (An, McAneny, Ridgway, Wise, 17, 17)



(Classical) Primordial Standard Clocks

Inflation or an alternative?

- Several alternative-to-inflation scenarios were also proposed;
  they suffer more theoretical problems and are more incomplete than Inflation;
  improvements are ongoing research activities

- Toy models of alternative-to-inflation act as a reminder
  that several key predictions of inflation may not be unique to the inflation scenario,
  and that there may be alternatives to inflation that should be explored and tested

- Even within inflation scenario, there are many predictions and observables;
  important to know which predictions distinguish inflation from possible alternative scenarios;
  which predictions distinguish different models of inflation.

Very few. (Tensor mode)
Always good to have complimentary approaches

The defining property of a scenario is the scale factor evolution: *a*(*t*)

Phenomenologically parameterize all scenarios by a power-law function $a(t) \sim t^p$ arbitrary p

Requiring quantum fluctuations exit horizon fixes the domain of *t* given *p*

$\lvert p\rvert > 1$	t: from 0 to $+\infty$	Fast expansion (Inflation) (Guth, 81, Linde, Albrecht, Steinhardt, 82)
$0 < p \sim \mathcal{O}(1) < 1$	t: from $-\infty$ to 0	Fast contraction (e.g. Matter contraction) (Wands, 98; Finelli, Brandenberger, 01)
$0 < p \ll 1$	t: from $-\infty$ to 0	Slow contraction (e.g. Ekpyrosis) (Khoury, Ovrut, Steinhardt, Turok, 01)
$-1 \ll p < 0$	t: from $-\infty$ to 0	Slow expansion (e.g. String gas cosmology) (Brandenberger, Vafa, 89)

Are there any observables that can directly measure $a(t)$?

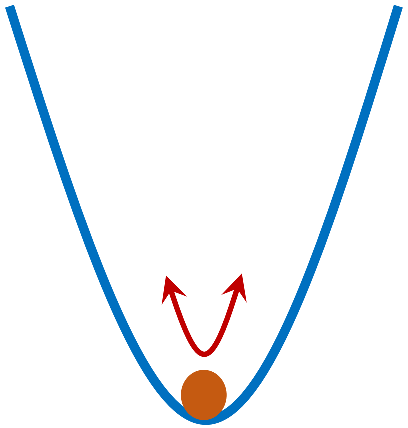
--- Clock signals by massive fields as primordial standard clocks

(XC: 1104.1323, 1106.1635;
XC, Namjoo, Wang: 1411.2349, 1509.03930)

Massive: Mass larger than event-horizon scale of the primordial epoch

Massive fields: 1) exist in any realistic models

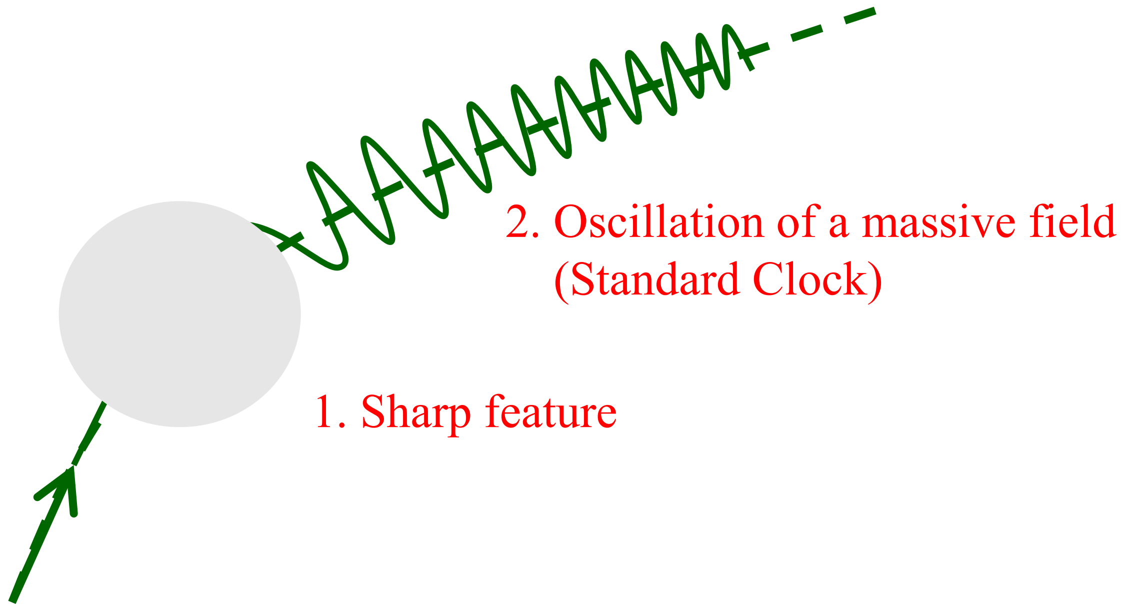
2) oscillate in a standard way in any background



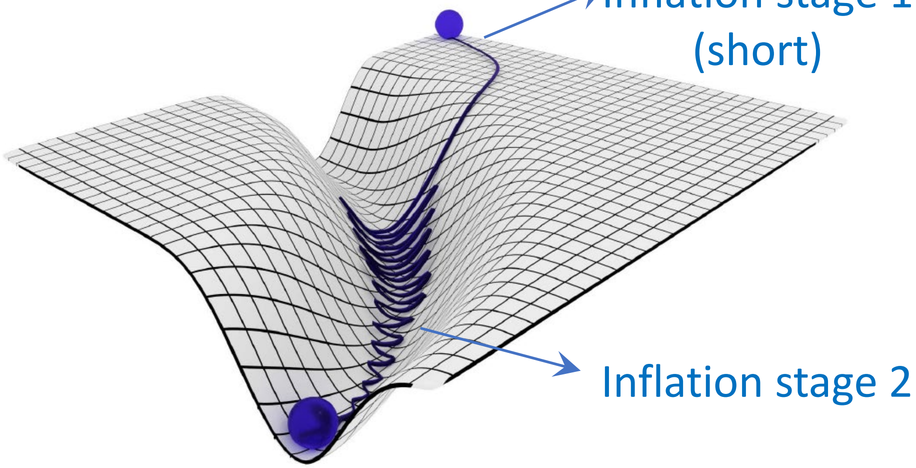
Oscillations provide ticks for the time coordinate t

Induce patterns of ticks in density perturbations – "**Clock Signals**"

(Classical) Primordial Standard Clocks



An example:



Massive field starts to oscillate classically due to some kind of kick (sharp feature)

Sharp features include: sharp turning, tachyonic falling, interactions, etc.

Sharp Feature Signal

$$\frac{\Delta P_\zeta}{P_{\zeta 0}} \propto 1 - \cos(2k_1\tau_0)$$ with model-dependent envelop/phase

Sinusoidal running is a signature of “sharp feature”;
but not a signature of massive field, **nor** does it record *a*(*t*).

Universal for different scenarios, i.e. independent of *p*

Nonetheless, an important component of full classical PSC signal.

The Clock Signal in Classical PSC

The background oscillation resonates with curvature fluctuations mode by mode

The clock signal: $$\sim \sin\left[p\frac{m}{m_{\mathrm{h},0}}\left(\frac{K}{k_r}\right)^{1/p}+\varphi\right]$$

$K \equiv k_1 + k_2 = 2k_1$ for power spectrum

horizon mass
at time of sharp feature

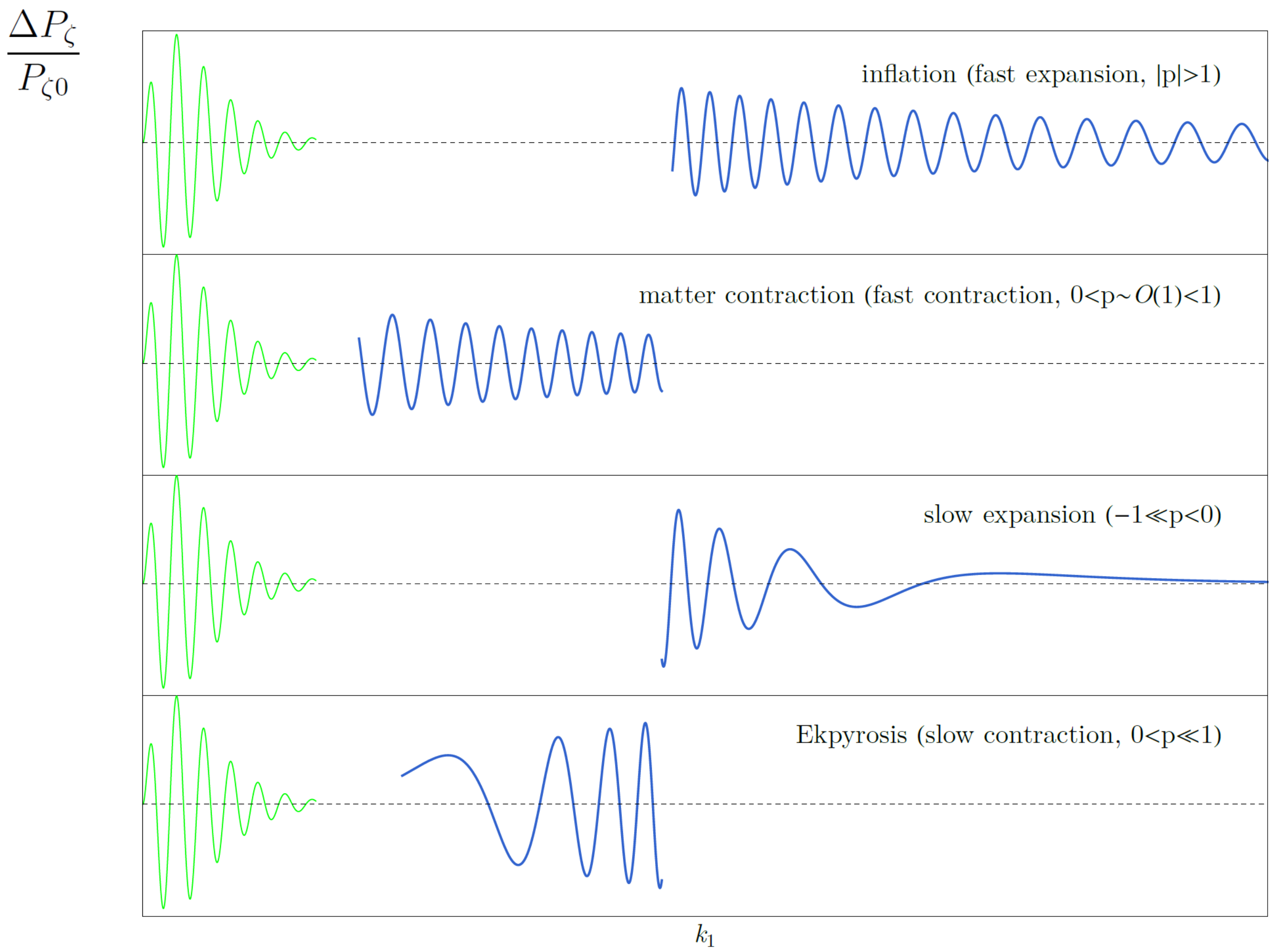
Inverse function of *a*(*t*)

$$a(t) = a_0\left(\frac{t}{t_0}\right)^p$$

This phase pattern is a direct measure of *a*(*t*)

Fingerprints of Different Scenarios

In both power spectra (as corrections) and non-Gaussianities

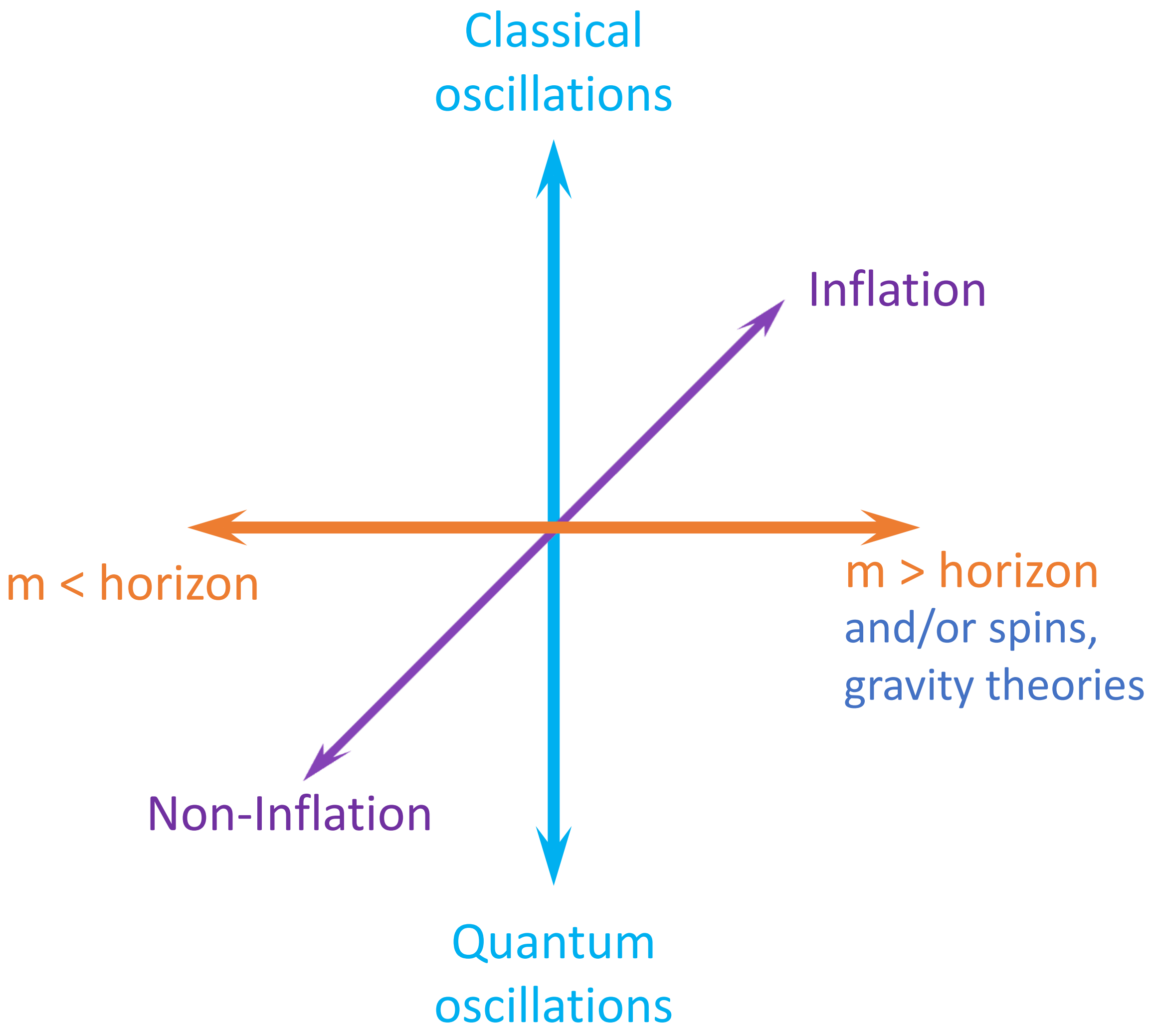


$$a(t) = a_0 \left(\frac{t}{t_0}\right)^p$$

Combine two directions

3D space of research projects

(high energy physics in density perturbations
or extended cosmological collider physics)



Two corners:

QSF and cosmological collider:
Inflation, quantum, small + large m

Classical primordial standard clocks:
Inflation + Non-inflation, classical, large m

Another corner:

Quantum primordial standard clocks:
Inflation + Non-inflation, quantum, (large) m

Others …….

A dynamical explanation of some soft limit properties

that is easy to generalize to non-inflationary backgounds

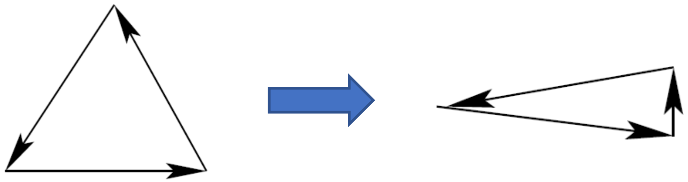
Quantum Oscillations of Massive Fields as Standard Clocks

For inflation (scale-invariant): Look for particle signals / clock signals in shape dependence of non-Gaussianities.

- scale-dependence:

Scale invariance → No clock signal in power spectrum (2pt)

- shape-dependence:



clock signal as a function of shape of non-Gaussianities

Condition for a Massive Field to be Qualified as a Quantum Clock

Classical Regime

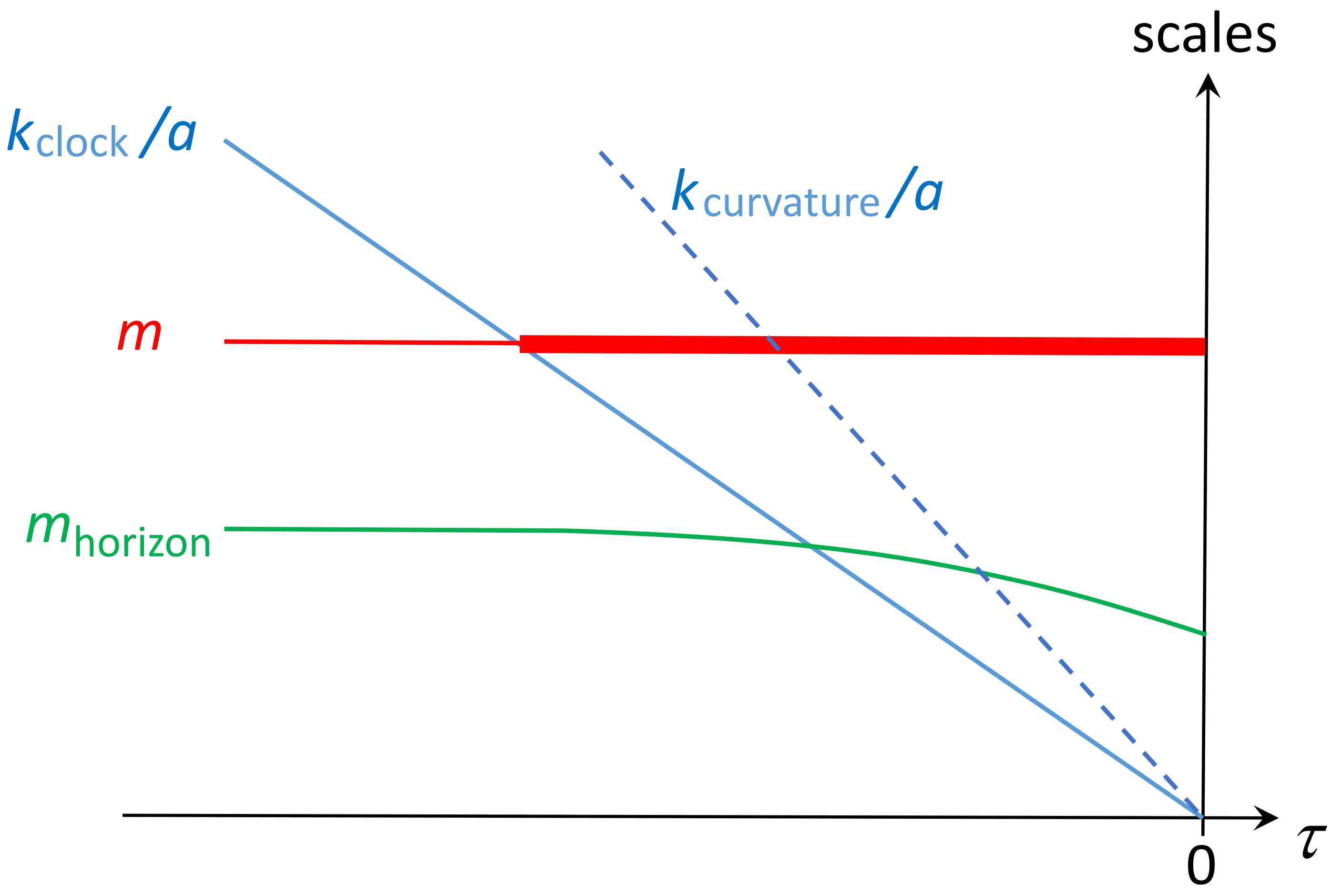
- Heavier than horizon scale: $m > m_{\rm h}$ $\quad m_{\rm h} \equiv \left|\frac{1-p}{t}\right| = \frac{1}{a|\tau|}$
- Homogeneous over Compton scale: $m > k/a$ exists either in the past or future

(Compton scale is the scale at which resonance happens)

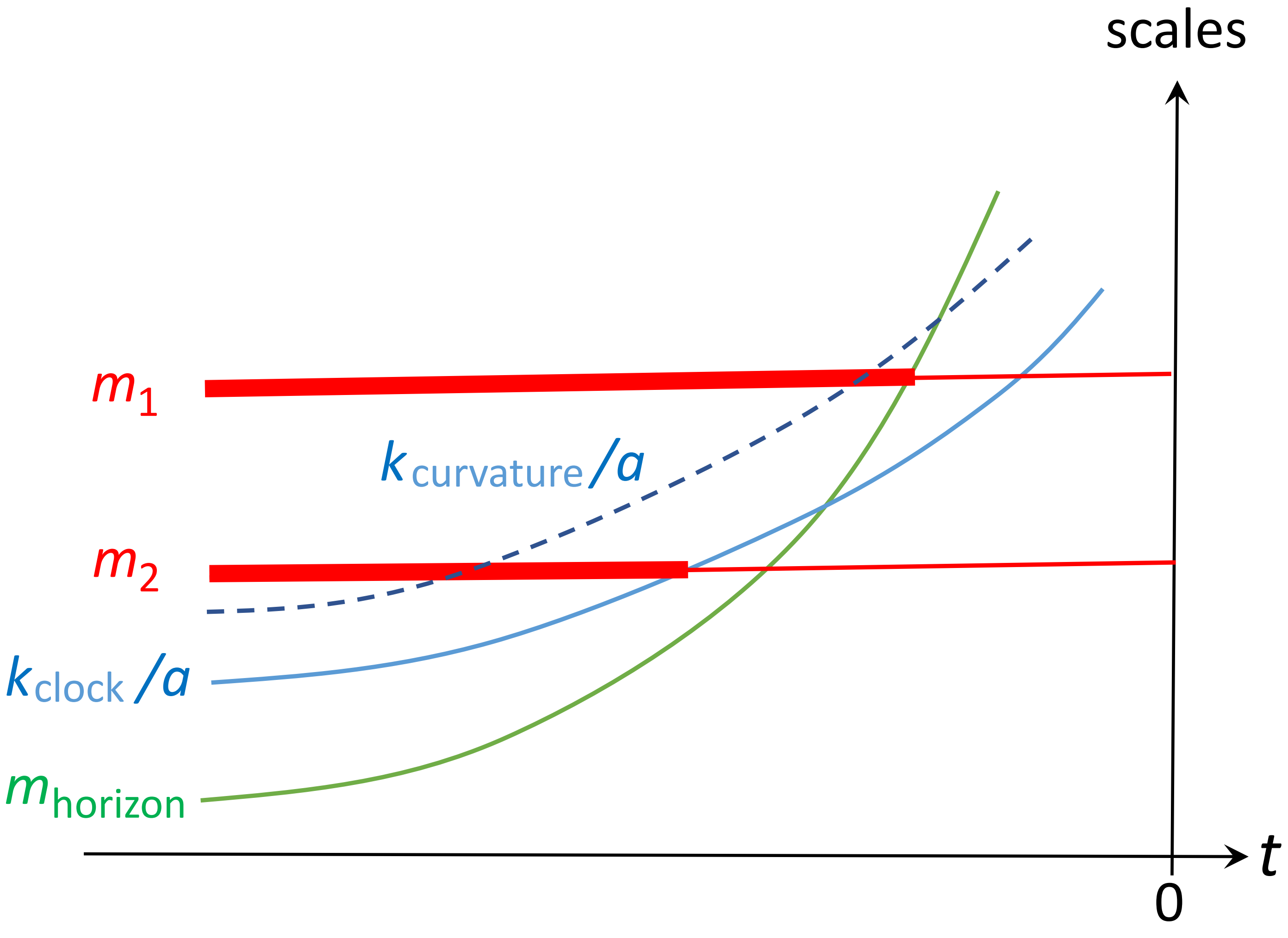
$$v_k \to \left(\frac{t}{t_k}\right)^{-3p/2} \left(c_+ e^{-imt} + c_- e^{imt}\right)$$

The quantum oscillation of massive is classical-like in the classical regime

Massive (Clock) Field in Inflation Scenario



Massive (Clock) Field in Contraction Scenarios



Generating Clock Signals 1

(XC, 11; XC, Namjoo, Wang, 15)

Standard clock oscillation: $\sigma \propto e^{\pm imt}$

Subhorizon curvature field oscillation: $\zeta_{\mathbf{k}} \propto e^{-ik\tau}$

$$dt = a d\tau$$

Correlation functions, e.g.: $\langle \zeta_{\mathbf{k}}^2 \rangle \supset \int e^{i(mt - 2k\tau)} d\tau$

The correlation receives leading contribution at the resonance point: $\frac{d}{dt}(mt - 2k\tau) = 0$

$\Rightarrow$ $\langle \zeta_{\mathbf{k}}^2 \rangle \supset e^{i(mt_* - 2k\tau_*)}$ $\qquad a(t_*) = a(\tau_*) = 2k/m$

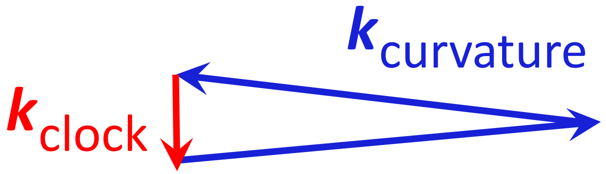
$$\langle \zeta_{\mathbf{k}}^2 \rangle \supset \exp\left[im\, t(2k/m) - 2ik\, \tau(2k/m) \right]$$

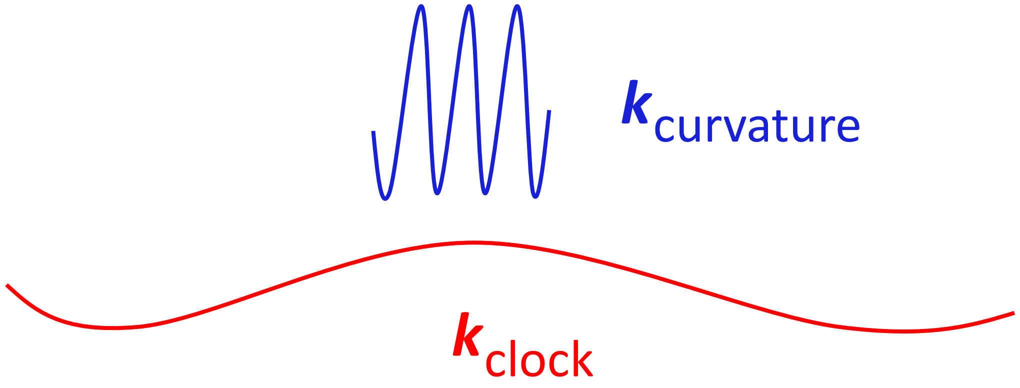
$t(2k/m)$ and $\tau(2k/m)$ are inverse functions of the scale factor $a(t)$ and $a(\tau)$

Scale factor as a function of time is directly encoded in the phase of the "clock signals" as a function of *k*

Quantum PSC in Arbitrary Scenarios

Quantum fluctuations of massive fields at the classical regime can serve as Standard Clocks





Longer wavelength quantum fluctuations of massive field
serve as background clock fields for shorter wavelength curvature mode

→ physics then becomes similar to the classical PSC case

The Clock Signal (Quantum Case) for Arbitrary Scenarios

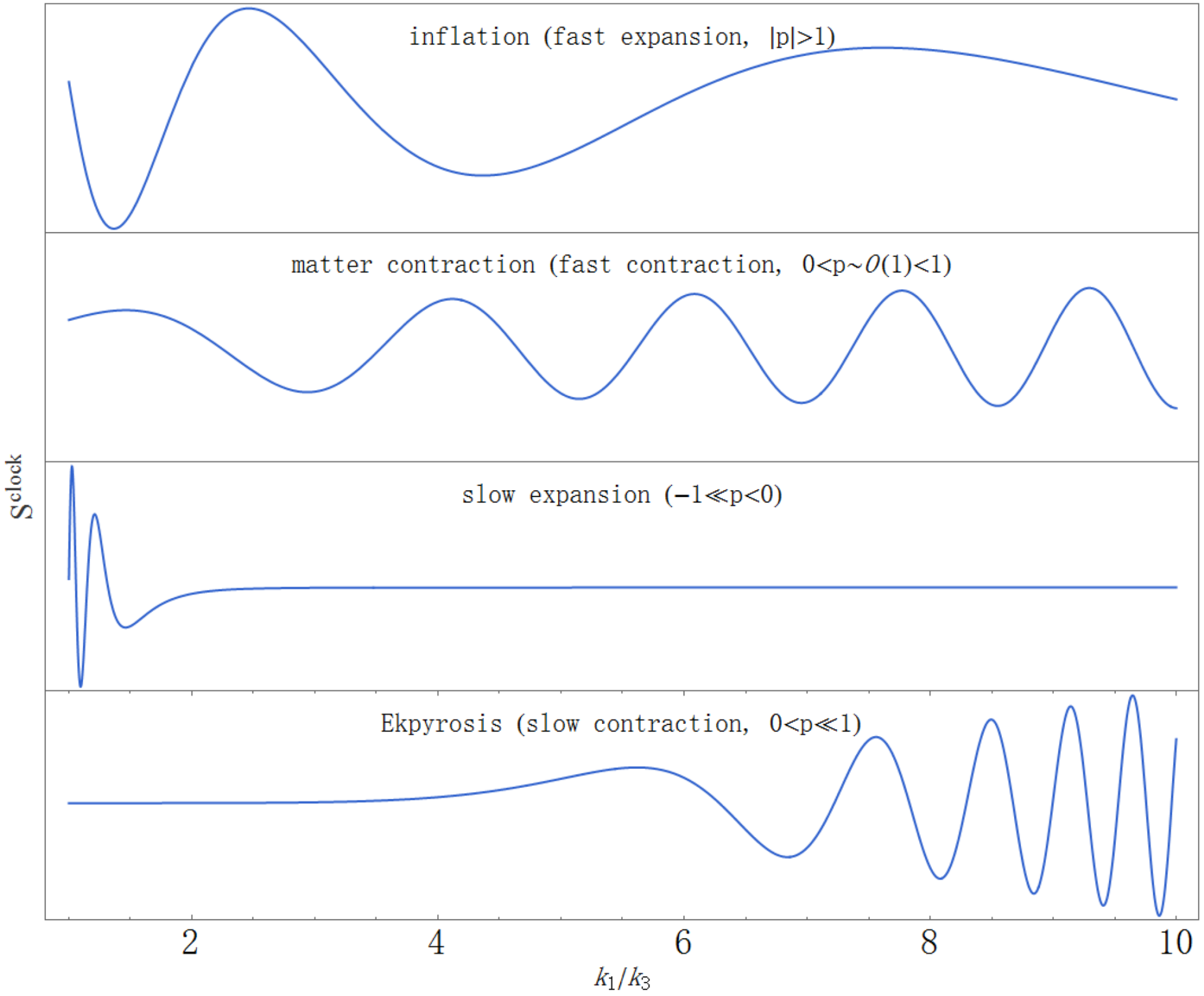
$$S^{\rm clock} \propto \left(\frac{2k_1}{k_3}\right)^{-\frac{1}{2}+\frac{1}{2p}} \sin\left[p\,\frac{m}{m_{{\rm h},k_3}}\left(\frac{2k_1}{k_3}\right)^{1/p} + \varphi(k_3)\right]$$

Inverse function of *a*(*t*)

k_3 : long mode $\qquad$ k_1 : short mode

Shape-dependent oscillatory signal that encodes $a(t)$

Fingerprints of Different Scenarios in Quantum SC



The Connection between Cosmological Collider Physics and QPSC

For *m>3H/2*, these signals directly encode the inflationary *a(t)*

$$S \propto \left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\frac{1}{2}\pm i\mu} \sim \left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\frac{1}{2}} \sin\left(\mu \ln \frac{k_{\rm long}}{k_{\rm short}} + {\rm phase}\right)$$

$\Downarrow$

Inverse function of exp

$\Downarrow$

Background is exponential inflation

So, cosmological collider is measuring not only the particle spectrum, but also the scale factor evolution of the inflationary background.

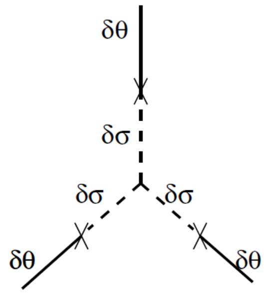
Amplitude of the Signals

The situation is very similar to the tensor mode

- Signal generically exists in models
- Amplitudes are highly model-dependent

For example, for inflation models:

- Gravitational coupling $f_{NL} < 0.01$
- Direct coupling $f_{NL} < 1$
- Massive fields self-coupling $f_{NL} < 100$
- Boltzmann suppression $\sim \exp(-\pi m/H)$



Signals of Massive Fields in Power Spectrum

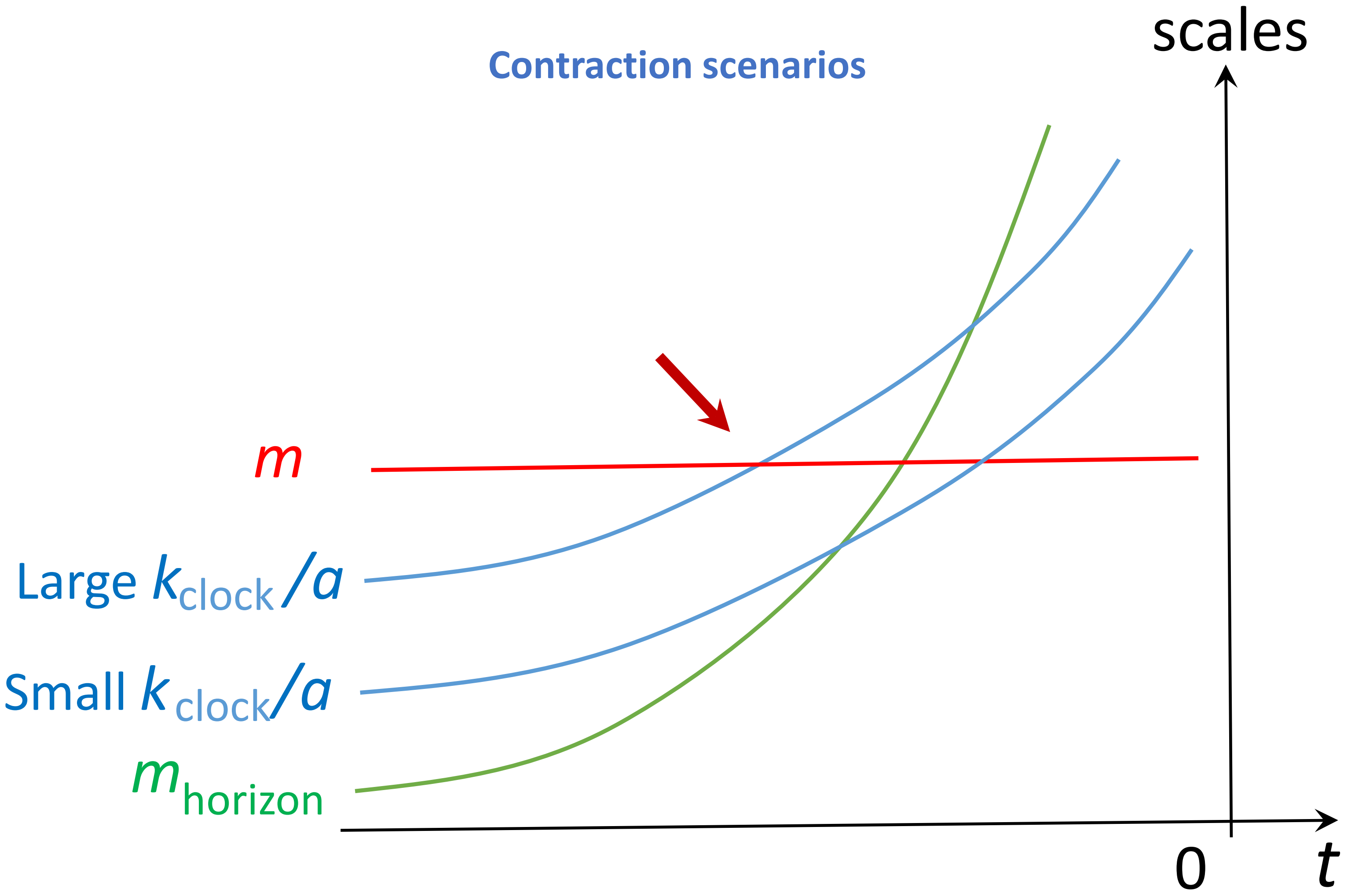
--- especially interesting for alternative scenarios to inflation

Only one momentum, no hierarchical scales, on resonance.

Look at the phase of the massive field mode function

E.O.M. for massive field model function: $$\ddot{v}_k + \frac{3p}{t}\dot{v}_k + \frac{k^2}{a^2}v_k + m^2 v_k = 0$$

Contraction scenarios



If k is large enough

$$\tilde{k} \equiv \frac{k/a}{m_{\mathrm{h}}}\left(\frac{m_{\mathrm{h}}}{m}\right)^{1-p} > 1$$

there is a crossover from *m*- to *k*-term

At late time, horizon always dominates

Generating Clock Signals 2

During the transition from the classical regime to k-dominated regime, the mode function develops a k-dependent phase that directly records a(t)

(XC, Loeb, Xianyu, 18)

$$\ddot{v}_k + \frac{k^2}{a^2} v_k + m^2 v_k \approx 0$$

$$v_k \sim \exp\left[\pm i m \int_{y_0}^{y} \sqrt{\frac{1}{z^2}+1} \, \frac{d a^{(-1)}\left(\frac{kz}{m}\right)}{dz} dz \right]$$

start with

$$v_k \propto \exp\left(\pm i m t\right)$$

contraction scenarios

upon entering k-dominated regime

$$v_k \propto \exp\left(\pm i \beta \tilde{k}^{1/p}\right) \exp\left(\pm i k \tau\right)$$

the clock signal: inverse function of *a*(*t*)

Similar conclusion holds for expansion scenarios

Condition: k small enough $\tilde{k} < 1$

Transition from *k*-dominated to *m*-dominated region

start with

$$v_k \propto \exp(\pm ik\tau)$$

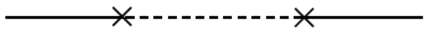
expansion scenarios

$\Longrightarrow$

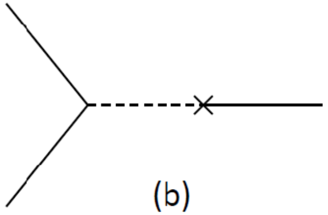
upon entering *m*-dominated regime

$$v_k \propto \exp\left(\mp i\beta\tilde{k}^{1/p}\right)\exp(\pm imt)$$

Clock Signal in Density Perturbations



(a)



(b)

$$\Delta\langle\zeta^2\rangle' = 2u_k^* u_k|_{\tau_{\rm end}} \left| \int_{-\infty}^{\tau_{\rm end}} d\tau \lambda_2(\tau) u_k v_k \right|^2$$
$$- 4{\rm Re}\left[u_k^2|_{\tau_{\rm end}} \int_{-\infty}^{\tau_{\rm end}} d\tau_1 \lambda_2(\tau_1) u_k^* v_k \int_{-\infty}^{\tau_1} d\tau_2 \lambda_2(\tau_2) u_k^* v_k^* \right]$$

In both classical regime and k-dominated regime, mode functions are oscillatory, so little contribution.

For alternative scenarios, main contribution comes from the horizon dominated regime.

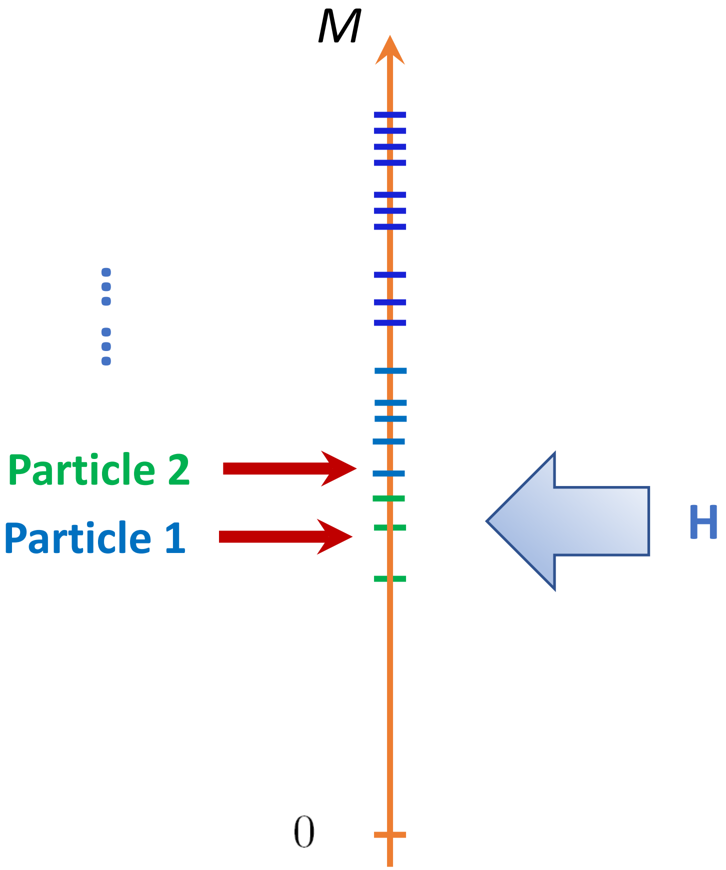
$$v_k \propto \exp\left(\pm i\beta \tilde{k}^{1/p}\right) \exp\left(\pm ik\tau\right)$$

time-independent clock signal phase factor

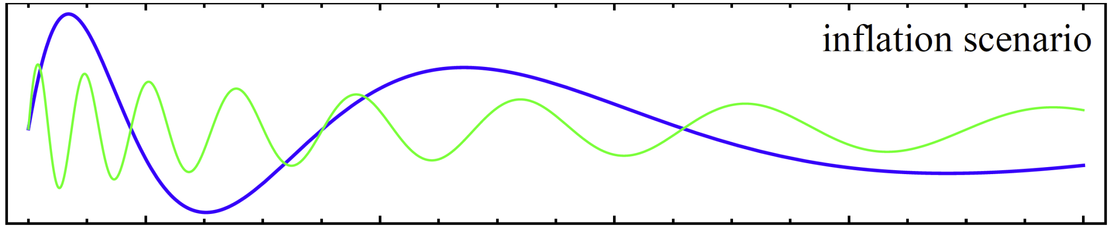
$$\Delta\langle\zeta^2\rangle' = |c_+ c_-^*| \sin\left(2\beta\tilde{k}^{1/p} + \phi\right) f(k) + \dots$$

the clock signal: inverse function of $a(t)$

Inflation: Cosmological Collider with Fixed Energy Scale (Quantum Case)

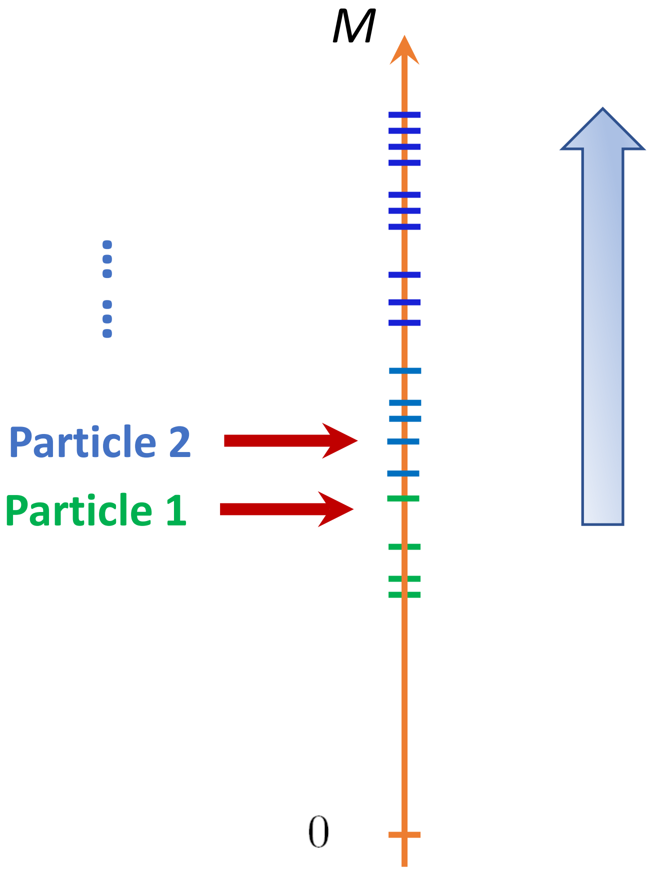


Mass spectrum

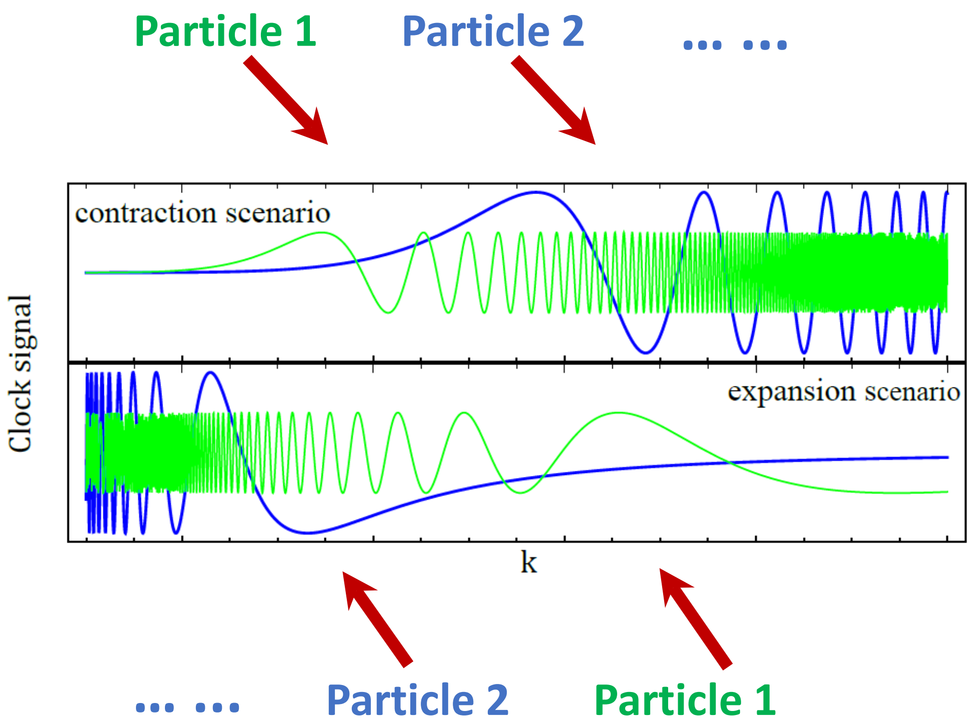


Energy scale of horizon is approximately constant;
Fields with mass below or around H are excited;
Signals of different particles lay on top of each other.

Alternatives to Inflation: Cosmological Particle Scanners



Mass spectrum



Scan over a tower of massive states one by one and display each of them as a pulse of signals at different length scales in the density perturbations.

Besides particle spectra,
signals from both types of particle detectors also carry direct information about $a(t)$
--- can be used to falsify competing scenarios in a model-independent fashion.

Some key properties that make these (both classical and quantum) primordial clocks "standard":

- Massive fields (with mass larger than horizon scale) oscillate like harmonic oscillators in any time-dependent background

- At resonance or during transition when clock signals are generated, quantum fluctuations of scalar curvature field are at sub-horizon scales.

  Sub-horizon behavior is standard --- Minkowski limit behavior;
  C.f. the super-horizon behavior of scalar field is very model-dependent.

Assumptions: mass of the clock is constant.

- How to mimic the signal with time-dependent mass or other features, and how to distinguish them

Non-Standard Primordial Clocks

Any repeated signals may be used as clocks – may confuse part of clock signals between different scenarios:

Examples of non-standard clocks:

$a(t) \sim t^p$ (arbitrary p)

engineer $B(t) \sim e^{ig\ln(t/t_0)}$ $\Rightarrow$ $\sin\left[\frac{g}{p-1}\ln\frac{K}{k_r} + \text{phase}\right]$ mimic Inflation-like oscillatory pattern

(XC, 01)

Look for other distinguishing characters against standard clocks

- Massive fields with time dependent mass

Non-inflation mimics inflation: $\xi R\sigma^2 \Rightarrow B(t) \sim e^{ig\ln(t/t_0)}$ (Wang, Wang, Zhu, 20)

Inflation mimics non-inflation: Field-dependent mass: $m^2(\phi)\chi^2$ (Huang, Pi, 16; Domenech, Rubio, Wons, 18)

1) Properties such as envelops of oscillations and other correlation functions are useful; 2) Extra parameters often needed

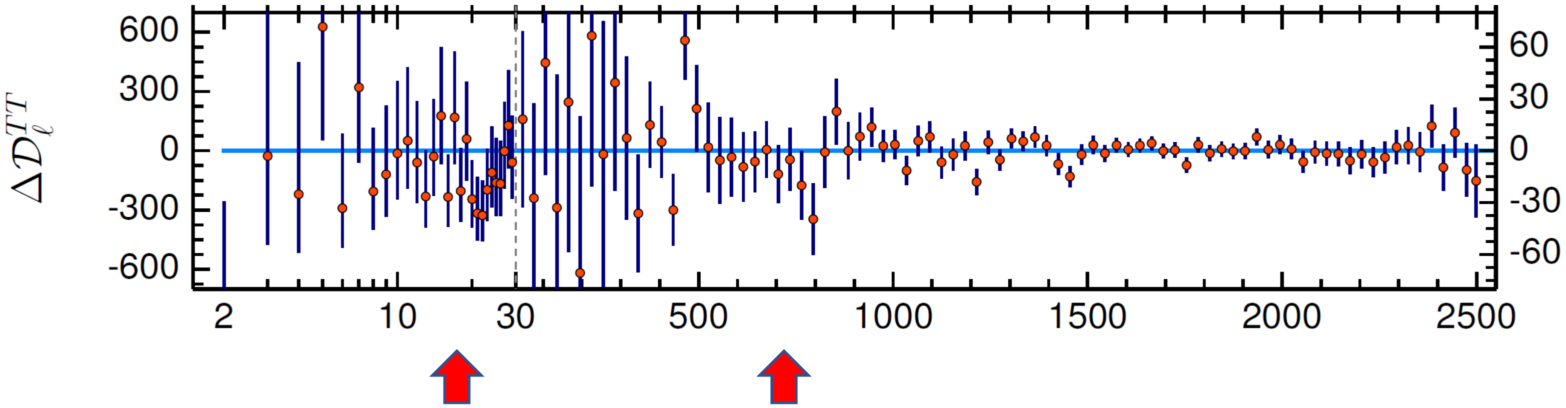
- Periodic or non-periodic ripples on inflationary potential (such as resonant models)

May be distinguished from massive fields by non-G, sharp feature signals, etc.

Data Comparison

There are some interesting, statistically marginal, anomalies in CMB residue data

(WMAP, Planck)



- Sharp feature model
- Resonance / axion monodromy model
- Classical primordial standard clock model
- Alternative to inflation $a \propto \tau^\alpha$ with $\alpha = 1.45 \pm 0.53$ (Domenech et al., 20)

Prospects for Future Observations

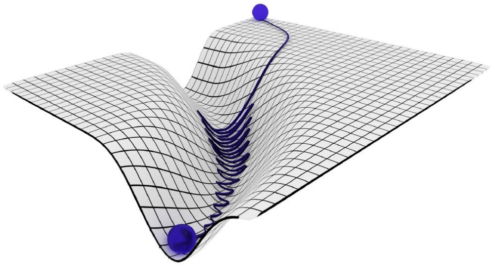
For scale-dependent primordial standard clocks , we look for correlated scale-dependent signals in :

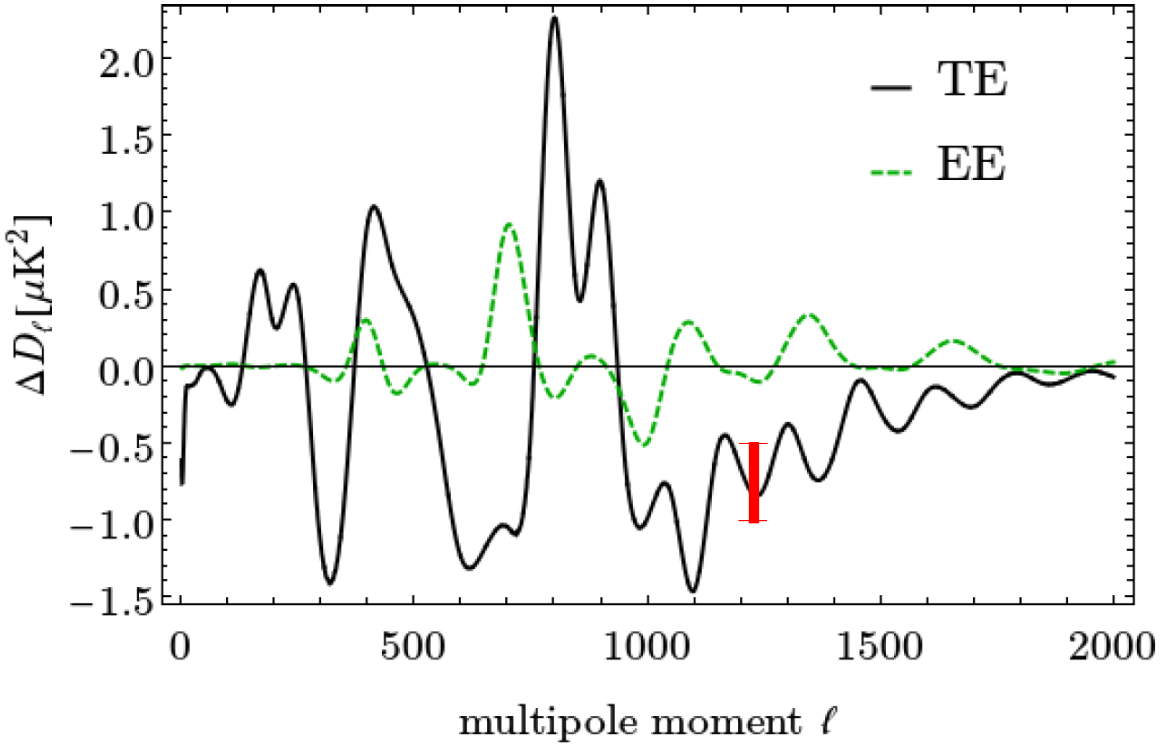
- All correlation functions:
  power spectrum and non-Gaussianities

- All manifestation of density fluctuations:
  CMB Temperature and Polarization, LSS, 21cm

Standard Clock models have strictly correlated signals in CMB polarization data

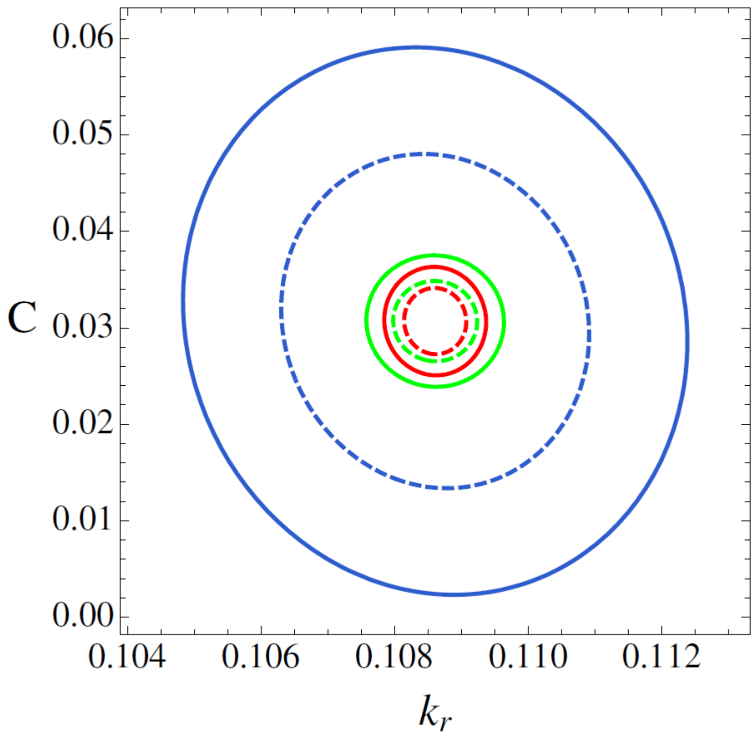
The classical
PSC example:

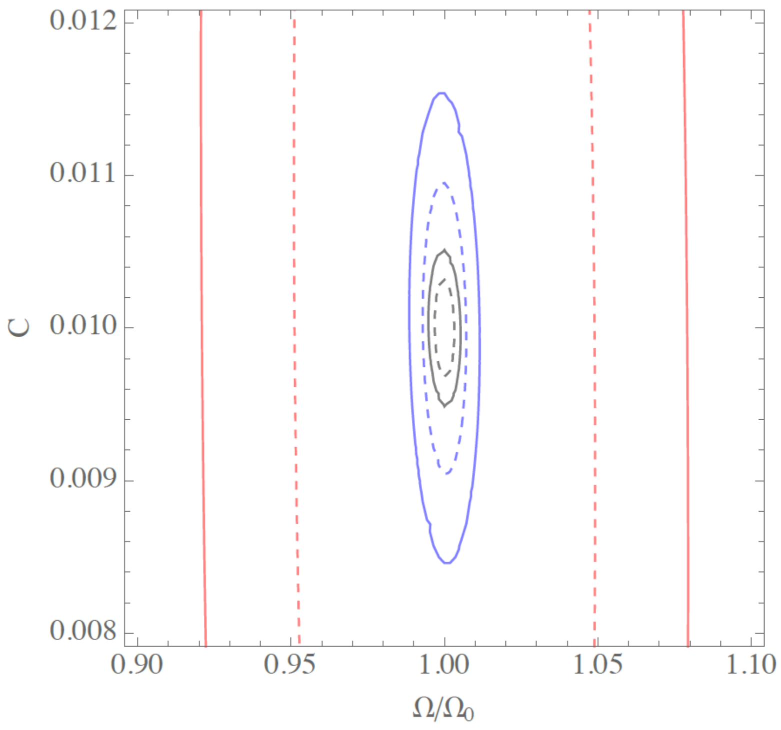




For TE, $\sigma(D_\ell) \approx 0.25\mu K^2$ with bin size $\Delta\ell = 30$

Correlated Signals in Large Scale Structure and 21cm Tomography





Planck Planck+LSST Planck+Euclid

A factor of 5 or more improvement on error

(XC, Dvorkin, Huang, Namjoo, Verde, 16; Beutler, Biagetti, Green, Slosar, Wallisch, 19)

21 cm experiment

may discover new features at much shorter scales

(*kr* = 0.01, 0.1, 1 /Mpc)

(XC, Meerburg, Munchmeyer, 16)

Large-scale structure surveys are also expected to better constrain clock signals from alternative scenarios to inflation

$$\frac{\Delta P_\zeta}{P_\zeta} = C \sin\left[p\Omega\left(\frac{2k}{k_r}\right)^{1/p} + \phi\right]$$

	$p=2/3$ $\Omega=30$ $k_r=0.1$	$p=2/3$ $\Omega=30$ $k_r=0.2$	$p=2/3$ $\Omega=100$ $k_r=0.1$	$p=1/5$ $\Omega=30$ $k_r=0.1$	$p=1/5$ $\Omega=30$ $k_r=0.2$	$p=1/5$ $\Omega=60$ $k_r=0.1$
σ_C	0.0016	0.0016	0.0016	0.0016	0.0017	0.0016
σ_p	0.0012	0.0033	0.00035	1.3×10^{-6}	3.8×10^{-5}	5.6×10^{-7}

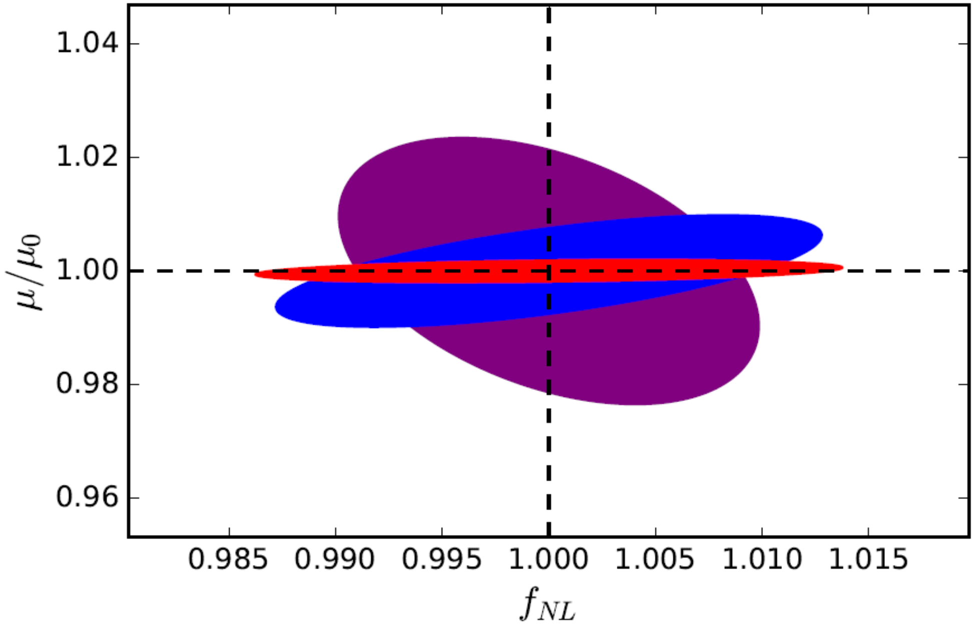
a LSST-like survey

(XC, Loeb, Xianyu, 18)

For shape-dependent primordial standard clocks, we look for correlated shape-dependent signals in non-Gaussian correlation functions

E.g. Cosmic Variance Limited 21cm Experiment with 30<z<100 and 100km baseline

Futuristic



μ = 0.7, 1.0, 3.0

$$\mu = \sqrt{(m/H)^2 - 9/4}$$

(Meerburg, Munchmeyer, Munoz, XC, 16)

Potential is great, how to realize such experiments is challenging

Thank You !