STRING THEORY
(AND GRAVITATIONAL WAVES)
IN THE FIRST HALF OF THE UNIVERSE

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Based on: *2401.04064 [Apers,Conlon,Copeland,Mosny,FR]*
24xx.xxxxx [Ghoshal,FR,Villa]

INTRODUCTION

Setting: String cosmology

See recent review [Cicoli,Conlon,Maharana,Quevedo,Parameswaran,Zavala '23]

Desiderata:
inflation, QCD axion,
quintessence, CC

→

Embed in
String Theory

←

This Talk

Steep potentials → *Kination,trackers*

What are typical dynamics induced by moduli potentials?

Are there any observable consequences?

THE FIRST HALF OF THE UNIVERSE (ON A LOG SCALE)

Early, exotic epochs:
- *Common in ST* — *Steep potentials*
- *<u>Require</u> ST* — $E_{\text{inflation}} \lesssim 10^{16}\ \text{GeV} \quad \Delta\phi \gtrsim M_P$

*Unconstrained by **current** observations* — *Huge opportunity for ST !*

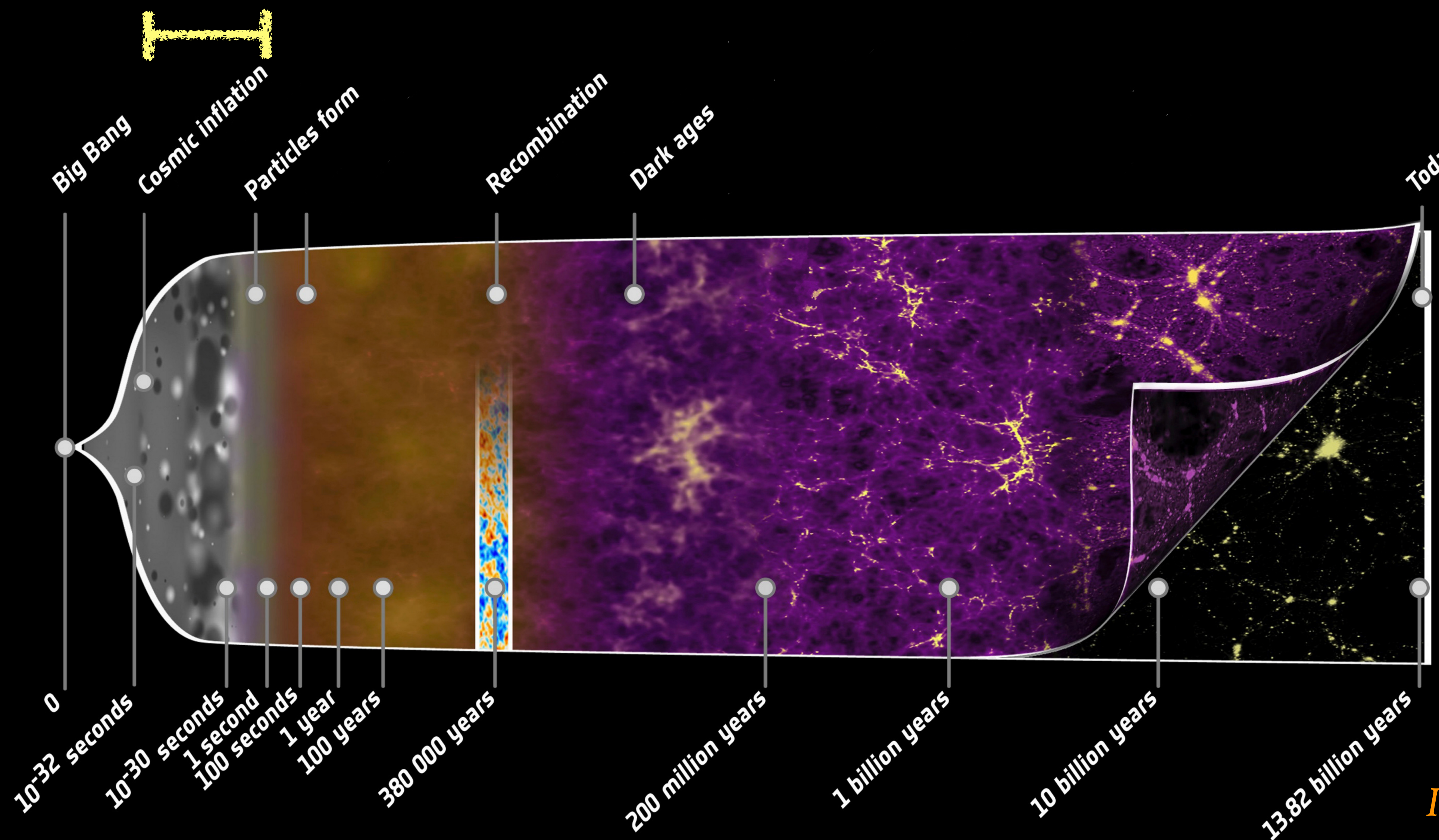


Image from ESA

KINATION

Scalar rolling down a steep potential: *'kination'* [Joyce '97]

$$\frac{1}{2}\dot{\phi}^2 \gg V(\phi) \qquad w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \simeq 1$$

Stiff fluid

$$\ddot{\phi} + 3H\dot{\phi} = -\cancel{\frac{\partial V}{\partial \phi}}$$

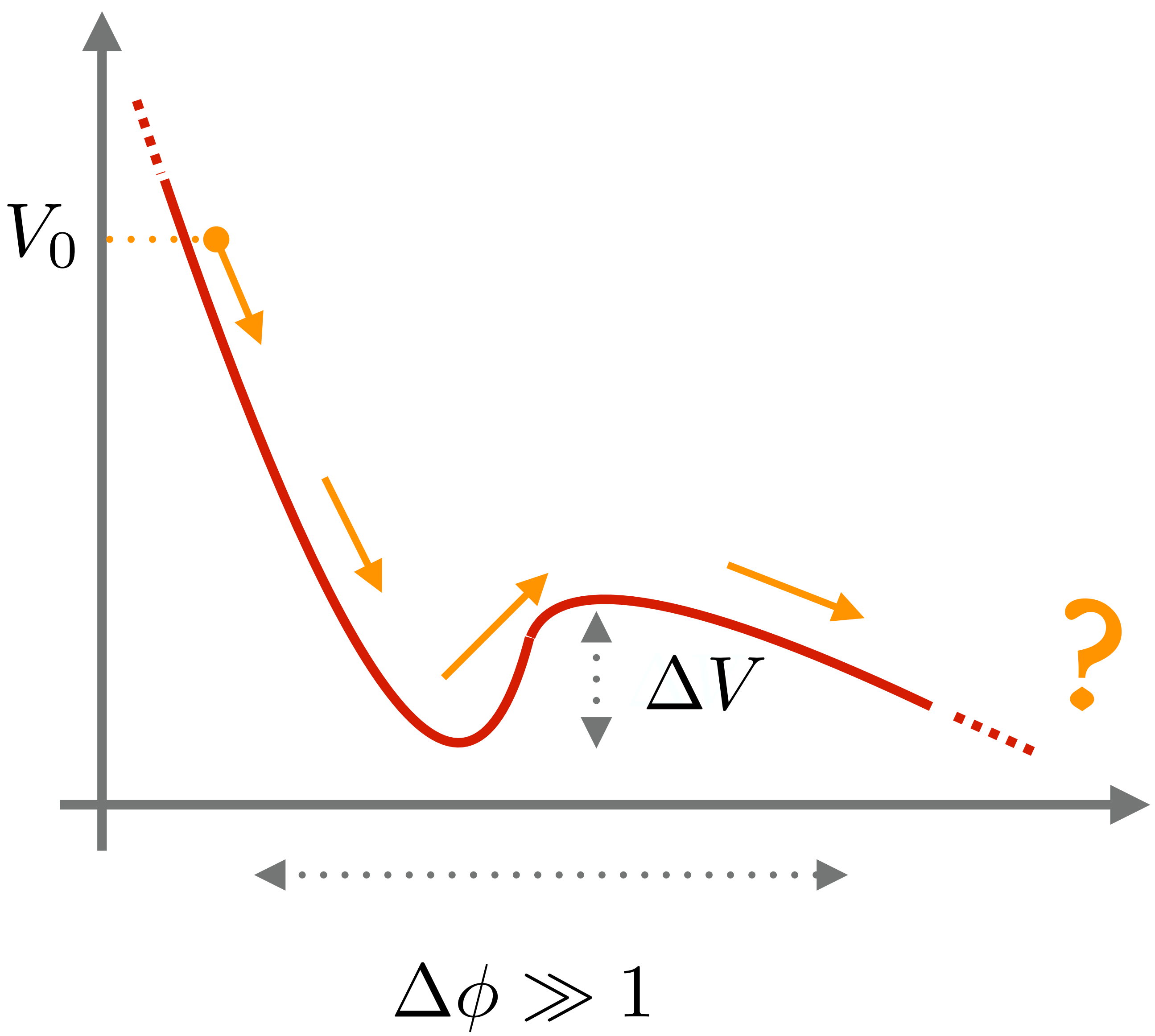
$$H^2 = \frac{1}{3M_P^2}\left(\cancel{V(\phi)} + \frac{1}{2}\dot{\phi}^2\right)$$

$$\phi(t) = \phi_0 + \sqrt{\frac{2}{3}}\underline{M_P}\ln\left(\frac{t}{t_0}\right) \qquad a(t) \sim t^{1/3}$$

inherently stringy

10 d "uplift": Kasner metric [Apers,Conlon,Mosny,FR'22]

KINATION IN OUR UNIVERSE



Steep asymptotic potentials

$$V(\Phi_i) \sim e^{-\lambda_i \Phi_i}$$

[Grimm,Li,Valenzuela '19]
+ many more

Specific example: *LVS (GKP)*

$$\Phi = \sqrt{\frac{2}{3}} \ln \mathcal{V}$$

[Conlon,Quevedo,Suruliz '05]
[Balasubramanian,Berglund,Conlon,Quevedo '05]

After inflation:

Other sources diluted

V_0 *high, as* $m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}$

TRACKER EPOCHS

Scalar field kinetic terms + potential 'tracking' fluid

$$3H^2 = \frac{1}{2}\dot{\Phi}^2 + V(\Phi) + \rho_\gamma + \frac{1}{2}e^{-\kappa\Phi}\dot{a}^2$$

All stay in constant ratios

Attractors

$$\rho \sim a^{-3(w_\gamma+1)}$$

as if only fluid present

Matter/radiation

[Wetterich '88]

[Copeland,Liddle,Wands '98; Ferreira,Joyce '98]

In LVS, only this kind

[FR'23]

Axions

[(Brinkmann),Cicoli,Dibitetto,Pedro'20 x 2, 22]

[FR'23]

acc. expansion?

Caveat: [Hebecker,Schreyer,Venken '23]

A NON-STANDARD PICTURE

Example of full cosmological history compatible with ST

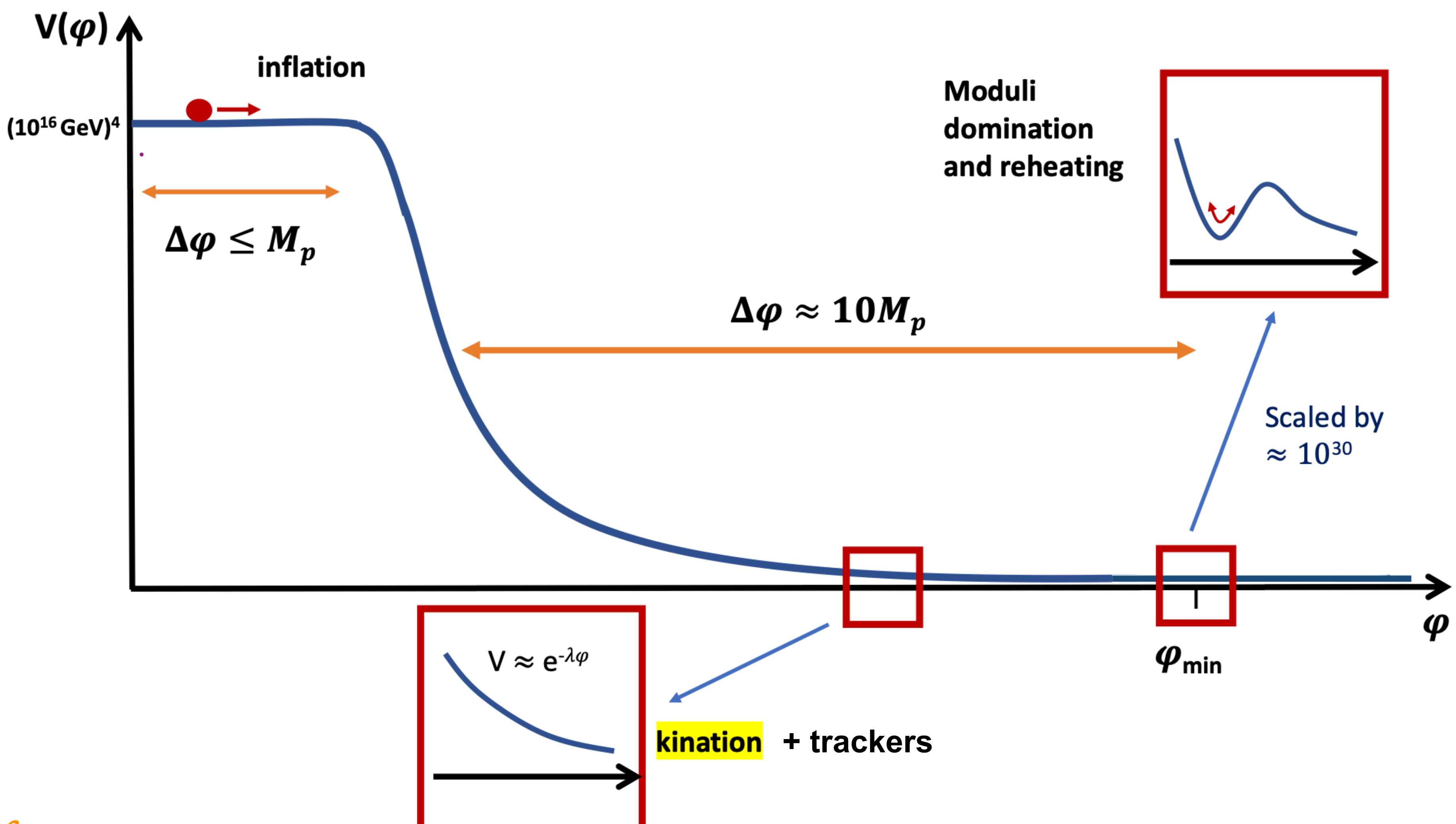


Figure from:

[Cicoli,Conlon,Maharana,Quevedo,Parameswaran,Zavala '23] [Apers,Conlon,Copeland,Mosny,FR '24]

Candidate: volume modulus in LVS

(In general $\neq$ inflaton!) E.g. waterfall field [Burgess,Quevedo '22]

COSMOLOGICAL PERTURBATIONS

Most general metric and matter pert. + gauge invariance

"Gravitational potential"

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

Gauge invariant variables

$$\Delta = \frac{\delta\rho}{\bar\rho} + v\frac{\bar\rho'}{\bar\rho}$$

"Density contrast"

Can be <u>significantly enhanced</u> in a non-standard epoch

<u>Very fast!</u>

E.g. Kination:

$$\Phi(\eta) = \frac{C_1}{k\eta}J_1(k\eta) + \frac{C_2}{k\eta}Y_1(k\eta) \longrightarrow a(\eta)\sin(k\eta), \quad k\eta \gg 1$$

$$\Delta(\eta) = -\frac{2iH_{\rm inf}}{M_P\sqrt{\varepsilon_V k^3}}\frac{k\eta J_1(k\eta)}{J_0(k\eta_0)} \longrightarrow a(\eta)^4, \quad k\eta \ll 1$$

[Apers,Conlon,Copeland,Mosny,FR'24]

TIME DEPENDENT COUPLINGS & COSMIC SUPERSTRINGS

Hallmark of String Theory: *couplings depend on moduli* $\Phi_i(t)$

Time dependent couplings $m_s \sim \dfrac{M_P}{\sqrt{\mathcal{V}(t)}}$

time dependent tension!

Cosmic fundamental strings *[Witten '85] [Polchinski '88] [Copeland,Myers,Polchinski '05]*

Conventional wisdom:

[Ghoshal,FR,Villa'24]

cosmic superstrings excluded by $G\mu = \left(\dfrac{m_s}{M_P}\right)^2 < 10^{-7}$ *(CMB)*

OK if $\mathcal{V} \gg 1$ ***after*** *CMB* ✓

Can be tested with ***Gravitational Waves***

Also at low frequency!

GRAVITATIONAL WAVES FROM COSMIC SUPERSTRINGS

Distinctive new pheno *from time dependent tension* $\mu(t)$ [Ghoshal,FR,Villa'24]

Long strings $\rho_{\text{strings}} = \frac{\mu}{L^2}$ $L = \xi t$ *Loops decay to GWs* $\frac{\mathrm{d}E}{\mathrm{d}t} = \Gamma G \mu^2$

energy in GWs *redshift*

$$\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\left|\frac{d\rho_{\rm GW}\,(f,t_0)}{df}\right| = \sum_k \frac{f}{\rho_c}\int_{t_F}^{t_0} d\tilde{t}\,\frac{dE_{\rm GW}}{d\tilde{t}}\,\frac{dn(\tilde{f},\tilde{t})}{d\tilde{f}}\left(\frac{a(\tilde{t})}{a\,(t_0)}\right)^3$$

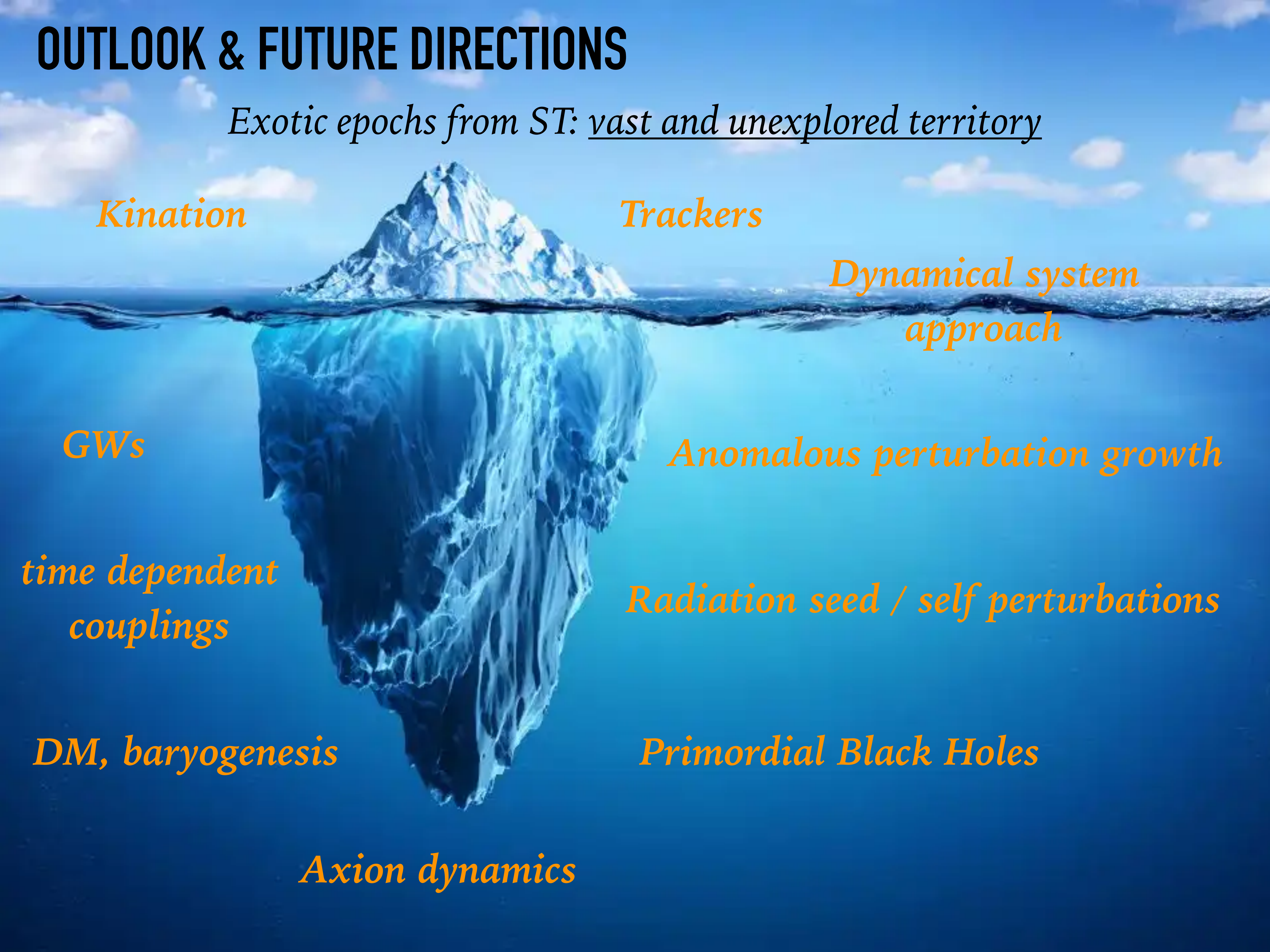
oscillator modes *loop production*

i) Information on cosmic history *E.g. volume kination* $\Omega_{GW} h^2 \sim f^5$

ii) GW emission extended in time *signal extends to low frequencies*

OUTLOOK & FUTURE DIRECTIONS

Exotic epochs from ST: vast and unexplored territory



Kination

Trackers

Dynamical system approach

GWs

Anomalous perturbation growth

time dependent couplings

Radiation seed / self perturbations

DM, baryogenesis

Primordial Black Holes

Axion dynamics

THANK YOU FOR YOUR ATTENTION!

WHAT ABOUT THE DISTANCE CONJECTURE?

Distance conjecture: $\Delta\phi \gg 1$ ⟷ *towers of light states* ↓ *Invalidate EFT*

[Ooguri, Vafa '06]
[Ooguri,Palti,Shiu,Vafa '19]

Kinematics

KK modes become light, but so do m_ϕ, Λ_ϕ ✓

Dynamics

$\boxed{\begin{array}{ll} \textit{KK modes above Hubble} & m_{KK}(t) \gg H(t) \\ \textit{Cutoff is adiabatic} & \left|\frac{\mathrm{d}\Lambda(t)_{KK}}{\mathrm{d}t}\right| \ll \Lambda(t)^2_{KK} \end{array}}$

✓

✓

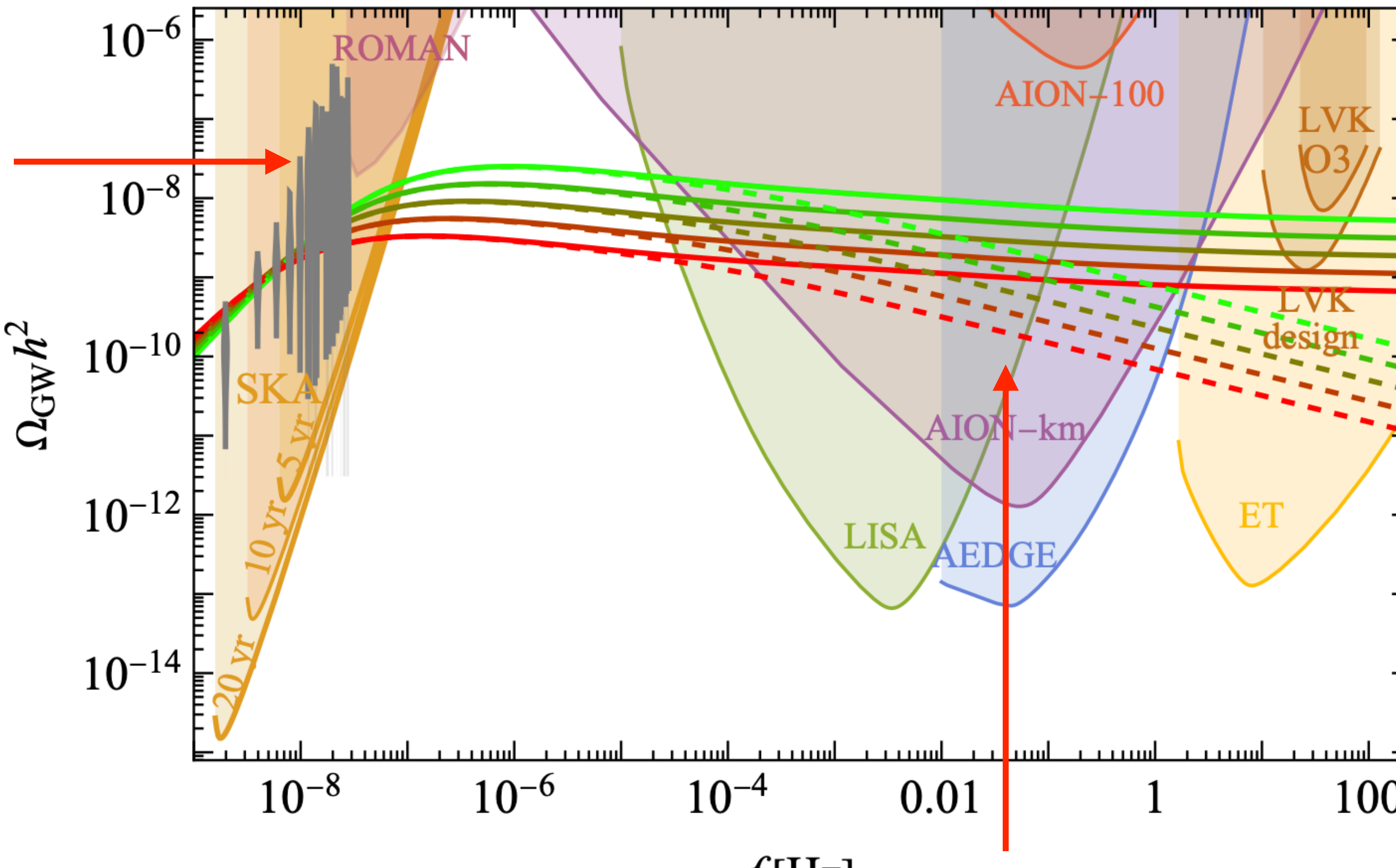
GW FROM COSMIC STRINGS

[Ellis, Lewicki,Lin,Vaskonen '23]

Different fits to Nanograv for cosmic superstrings

$G\mu \sim 10^{-11} - 10^{-12}$

$P \sim 10^{-1} - 10^{-3}$



Early matter domination up to BBN

For LVS

$$t_{\rm reh} \sim \frac{1}{\Gamma_\Phi} = \left(\frac{1}{4\pi}\frac{m_\Phi^3}{M_P^2}\right)^{-1}$$

Predicts deviation!

THE BACKGROUND COSMOLOGY

Epoch	a(t)	η	Range of η	$\mathcal{H} = \frac{a'(\eta)}{a(\eta)}$	PE:KE:Rad
Inflation	$e^{H_{inf}t}$	$\sim -e^{-Ht}$	$-\infty < \eta \lesssim 0 \sim \eta_0$	H_{inf}	$\frac{1}{2}$:$\frac{1}{2}$:ϵ (at end)
Kination	$t^{1/3}$	$\eta \sim t^{2/3}$	$\eta_0 \lesssim \eta \lesssim \frac{\eta_0}{\epsilon}$	$\frac{1}{2\eta}$	$\epsilon^{3/2} : \frac{1}{2} : \frac{1}{2}$ (at end)
Radiation domination: PE $\leq$ KE	$t^{1/2}$	$\eta \propto t^{1/2}$	$\frac{\eta_0}{\epsilon} \lesssim \eta \lesssim \frac{\eta_0}{\epsilon^{5/4}}$	$\frac{1}{\eta}$	$\epsilon^{1/2}$:$\epsilon^{1/2}$:1 (at end)
Radiation domination: PE $\geq$ KE	$t^{1/2}$	$\eta \propto t^{1/2}$	$\frac{\eta_0}{\epsilon^{5/4}} \lesssim \eta \lesssim \frac{\eta_0}{\epsilon^{11/8}}$	$\frac{1}{\eta}$	$\frac{1}{2}$:$\epsilon^{3/4}$:$\frac{1}{2}$ (at end)
Tracker	$t^{1/2}$	$\eta \propto t^{1/2}$	$\frac{\eta_0}{\epsilon^{11/8}} \lesssim \eta \lesssim m_\Phi^{-1/2}$	$\frac{1}{\eta}$	$\frac{3(2-\gamma)\gamma}{2\lambda^2}$:$\frac{3\gamma^2}{2\lambda^2}$: $1-\frac{3\gamma}{\lambda^2}$
Matter domination	$t^{2/3}$	$\eta \propto t^{1/3}$	$m_\Phi^{-1/2} \lesssim \eta \lesssim \Gamma_\Phi^{-1/2}$	$\frac{2}{\eta}$	NA
Reheating to Standard Model	$t^{1/2}$	$\eta \propto t^{1/2}$	$\eta \gtrsim \Gamma_\Phi^{-1/2}$	$\frac{1}{\eta}$	0:0:1 (at end)

[Apers,Conlon,Copeland,Mosny,FR '24]

Analytical treatment of transition epochs

Eg: kination to radiation domination:

$$a(\eta) = a_0 \sqrt{\frac{\eta}{\eta_0} + \frac{\varepsilon}{4}\left(\frac{\eta}{\eta_0}\right)^2} \qquad \mathcal{H}(\eta) = \frac{1}{2\eta}\frac{1+\frac{\varepsilon\eta}{2\eta_0}}{1+\frac{\varepsilon\eta}{4\eta_0}}$$

Useful to analyse e.g. perturbations

EQUATIONS OF MOTION

$$
\begin{cases}
\ddot{\phi}^i + \Gamma^i_{jk}\dot{\phi}^j\dot{\phi}^k + (d-1)H\dot{\phi}^i + \partial^i V = 0 \\[2ex]
\dfrac{(d-1)(d-2)}{2}H^2 = \dfrac{1}{2}G_{ij}\partial_\mu\phi^i\partial^\mu\phi^j - V\left(\phi^i\right) + \rho_\gamma \\[2ex]
\dot{\rho}_\gamma + 3\gamma H\rho_\gamma = 0
\end{cases}
$$

Generic fluid:
matter, radiation…

Asymptotics of moduli space *(large Vol, CS moduli…)*

$$
G_{ij,I} = C_I \frac{\delta_{ij}}{\left(s^I\right)^2} \qquad V\left(s^I, a^I\right) = V_0 \prod_{I=1}^{N} \frac{1}{\left(s^I\right)^{\lambda_I}}
$$

Simpler expressions, analytic treatment

DYNAMICAL SYSTEM REFORMULATION

$$x_i = \sqrt{\frac{C_i}{(d-1)(d-2)}}\,\frac{\dot{s}_i}{H s_i} \qquad y_i = \sqrt{\frac{C_i}{(d-1)(d-2)}}\,\frac{\dot{a}_i}{H s_i} \qquad w = \frac{1}{H}\sqrt{\frac{2\rho_\gamma}{(d-1)(d-2)}}$$

saxions *axions* *fluid*

$$\left\{\begin{aligned}
\frac{dx_i}{dM} &= -\sqrt{\frac{(d-1)(d-2)}{C_i}}\left[{y_i}^2 - \frac{\lambda_i}{2}\left(1 - \sum_{j=1}^{N}\left({x_j}^2 + {y_j}^2\right) - w^2\right)\right] \\
&\quad - x_i(d-1)\left(1 - \sum_{j=1}^{N}\left({x_j}^2 + {y_j}^2\right) - \frac{\gamma}{2}w^2\right) \\
\frac{dy_i}{dM} &= \sqrt{\frac{(d-1)(d-2)}{C_i}}\,x_i y_i - (d-1)\left(1 - \sum_{j=1}^{N}\left({x_j}^2 + {y_j}^2\right) - \frac{\gamma}{2}w^2\right) y_i \\
\frac{dw}{dM} &= (d-1)w\left[\sum_{j=1}^{N}\left({x_j}^2 + {y_j}^2\right) + \frac{\gamma}{2}\left(w^2 - 1\right)\right]
\end{aligned}\right.$$

[Copeland,Liddle,Wands '98], [Collinucci,Nielsen, Van Riet '04]
[(Brinkmann),Cicoli,Dibitetto,Pedro'20 x2, 22],[Shiu,Tonioni,Tran '23] x 3, [FR '23]…

COSMOLOGICAL PERTURBATIONS 1

Most general metric and matter pert. + gauge invariance

Newtonian gauge:* *"Gravitational potential"*

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

$$T^0_{\ 0} \equiv -(\bar\rho + \delta\rho) \quad T^0_{\ i} \equiv (\bar\rho + \bar P)\partial_i v \quad T^i_{\ j} \equiv (\bar P + \delta P)\delta^i_{\ j}$$

Figure taken from [Baumann '22]

Gauge invariant variables

$$\boxed{\begin{gathered}\Phi \\ \Delta = \frac{\delta\rho}{\bar\rho} + v\frac{\bar\rho'}{\bar\rho}\end{gathered}}$$

Table 6.1 Summary of the evolution of cosmological perturbations.

		radiation era	matter era
Φ	$k < \mathcal{H}$	const	const
	$k > \mathcal{H}$	$a^{-2}\cos(k\eta/\sqrt{3})$	const
Δ_r	$k < \mathcal{H}$	a^2	a
	$k > \mathcal{H}$	$\cos(k\eta/\sqrt{3})$	$\cos(k\eta/\sqrt{3}) + \mathrm{const}$
Δ_m	$k < \mathcal{H}$	a^2	a
	$k > \mathcal{H}$	$\ln a$	a

COSMOLOGICAL PERTURBATIONS 2

Solve perturbed Einstein Eqs

$$\nabla^2\Phi - 3\mathcal{H}\left(\Phi' + \mathcal{H}\Phi\right) = \frac{a^2}{2M_P^2}\left(\delta\rho_k + \delta\rho_p + \delta\rho_f\right)$$

$$\Phi'' + 3\mathcal{H}\Phi' + \left(2\mathcal{H} + \mathcal{H}^2\right)\Phi = \frac{a^2}{2M_P^2}\left(\delta\rho_k - \delta\rho_p + (\gamma - 1)\delta\rho_f\right)$$

+ scalar field EOMs

$$\delta\phi_k'' + 2\mathcal{H}\delta\phi_k' + k^2\delta\phi_k + \lambda^2 a^2\frac{V(\phi)}{M_P^2}\delta\phi_k = 4\phi'\Phi_k' + 2\lambda a^2\frac{V(\phi)}{M_P}\Phi_k$$

Sub-horizon ← *Analytic solutions* → *Super-horizon*

$k\eta \gg 1$ $\qquad$ $k\eta \ll 1$

COSMOLOGICAL PERTURBATIONS - RESULTS

Kination:

Very fast!

$$\Phi(\eta) = \frac{C_1}{k\eta} J_1(k\eta) + \frac{C_2}{k\eta} Y_1(k\eta)$$

$$\Delta(\eta) = -\frac{2iH_{\text{inf}}}{M_P\sqrt{\varepsilon_V k^3}} \frac{k\eta J_1(k\eta)}{J_0(k\eta_0)}$$

$a(\eta)\sin(k\eta), \quad k\eta \gg 1$

$a(\eta)^4, \quad k\eta \ll 1$

Radiation Tracker: $k\eta \gg 1$

Very similar to radiation domination, O(1) diff

$$\Phi(\eta) \simeq \frac{C_3 \sin\left(\frac{k\eta}{\sqrt{3}}\right) + C_4 \sin(k\eta + C_5)}{a(\eta)^2} \qquad \Delta \simeq C_3 \sin\left(\frac{k\eta}{\sqrt{3}}\right) + C_4 \sin(k\eta + C_5)$$

Matter Tracker: $k\eta \gg 1$

Unlike matter domination, depends on λ

$$\Phi \simeq C_6 a(\eta)^{\frac{1}{4}\left(\frac{\sqrt{25\lambda^2-72}}{\lambda}-5\right)} \sim \underbrace{a(\eta)^{-0.14}}_{\text{LVS}} \qquad \Delta \simeq C_7 a(\eta)^{\frac{1}{4}\left(\frac{\sqrt{25\lambda^2-72}}{\lambda}-1\right)} \sim \underbrace{a(\eta)^{0.86}}_{\text{LVS}}$$

+ *various analytical results for transient epochs*