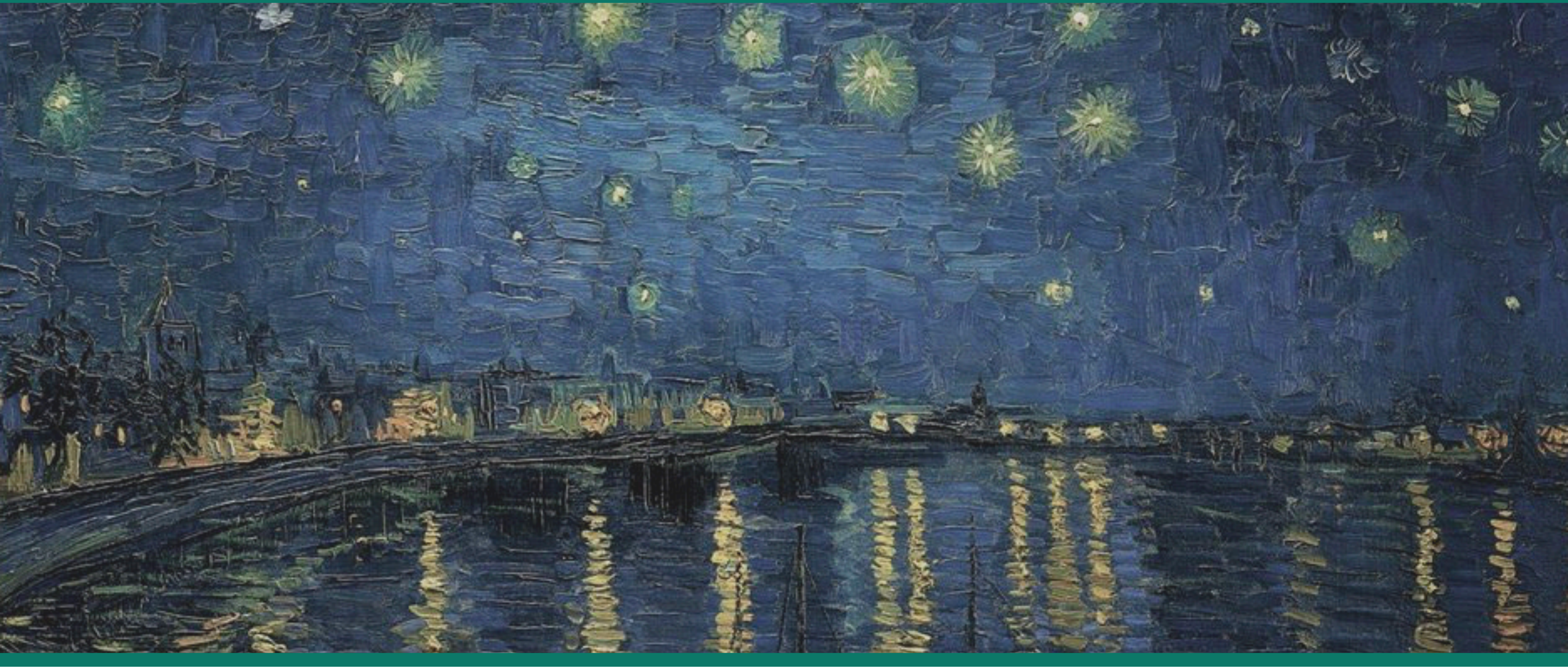


Quantum Gravity Constraints on Cosmic Acceleration

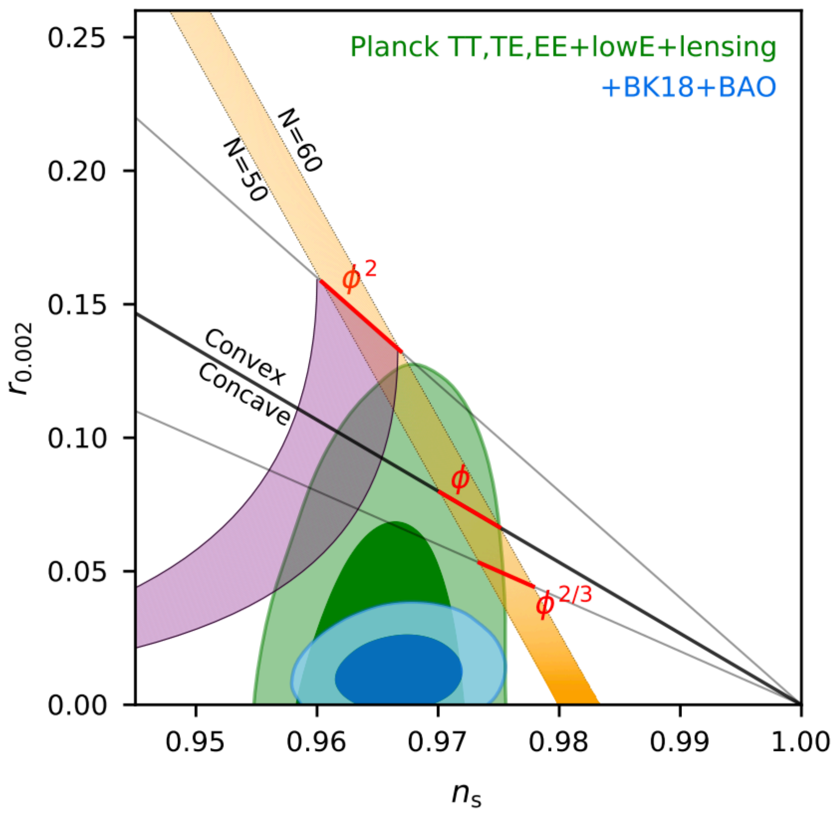
based on

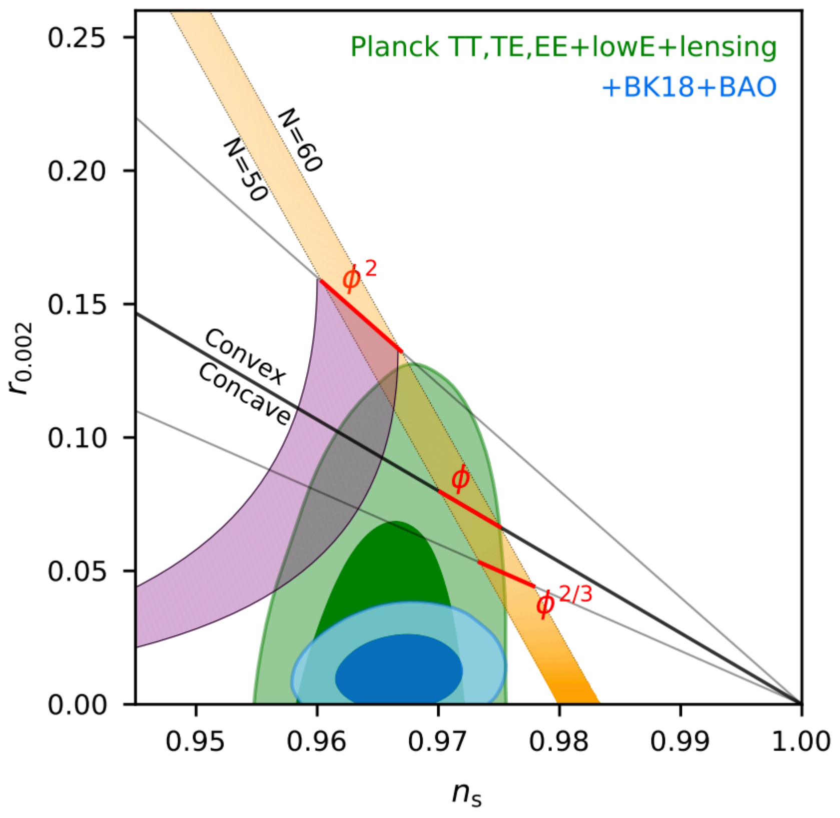
2306.17217, J.Freigang, D. Lüst, G. Nian, MS
work in progress, D. Lüst, J. Masias, M. Pieroni, MS

Marco Scalisi

July 3rd, 2023
String Pheno Conference 2023 - Daejeon

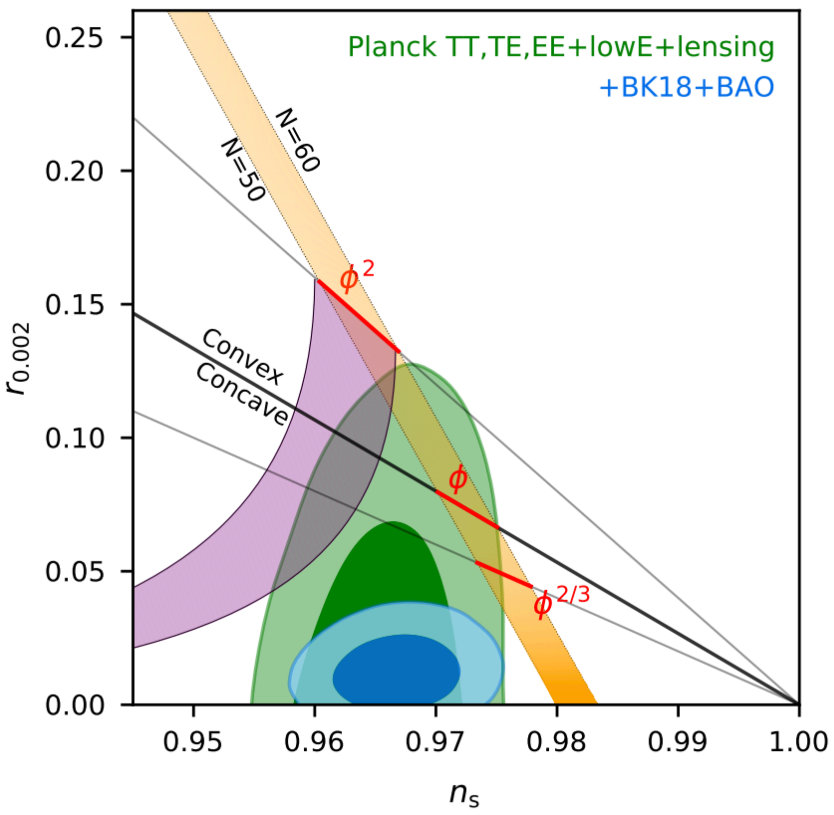
MAX-PLANCK-INSTITUT
FÜR PHYSIK


Planck TT,TE,EE+lowE+lensing
+BK18+BAO
N=60
N=50
ϕ^2
Convex
Concave
ϕ
$\phi^{2/3}$
0.25
0.20
0.15
0.10
0.05
0.00
$r_{0.002}$
0.95
0.96
0.97
0.98
0.99
1.00
n_s



$$r < 0.035$$

$$\boxed{H \lesssim 10^{-5}\ M_{\rm P}}$$



$r < 0.035$

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Swamplang Program

$$\Lambda_{QG} < M_P$$

One lesson of the **Swampland Program**

Swampland constraints tend to assume **more relevance** in **extreme regimes of the parameter space** of the theory

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Weak Gravity Conjecture *Arkani-Hamed et al 2006*	→ small **gauge coupling**
Swampland Distance Conjecture *Ooguri, Vafa 2006*	→ large **distances**
AdS Distance Conjecture *Lüst, Palti, Vafa 2019*	→ small **value of the (AdS) CC**
Gravitino Conjecture *Cribiori, Lüst, **MS** '21 - Castellano et al '21*	→ small **gravitino mass**

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Swampland Distance Conjecture

Ooguri, Vafa 2006

"Infinite scalar field variations Δ are always associated to (at least) an infinite tower of states becoming exponentially light"

$$m \sim m_0 e^{-\lambda\Delta} \qquad\qquad \Delta \to \infty$$

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quantum gravity cut-off = "**species scale**"

Dvali 2007

Dvali, Redi 2007

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see talks by
Herraez, Castellano, Cribiori, D. Lüst, Wiesner, Valenzuela

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exponential drop-off of the QG cut-off

$$\Lambda_{QG} = \Lambda_0 e^{-\gamma\Delta}$$

$\Lambda_0 \leq M_P$
original naive cut-off

Outline of the talk

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- Constraint on the **total scalar field range** - - - - - - - -> $\Delta \lesssim -\log H$

  MS, Valenzuela 2018

  MS 2019

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  Freigang, Lüst, Nian, MS 2023

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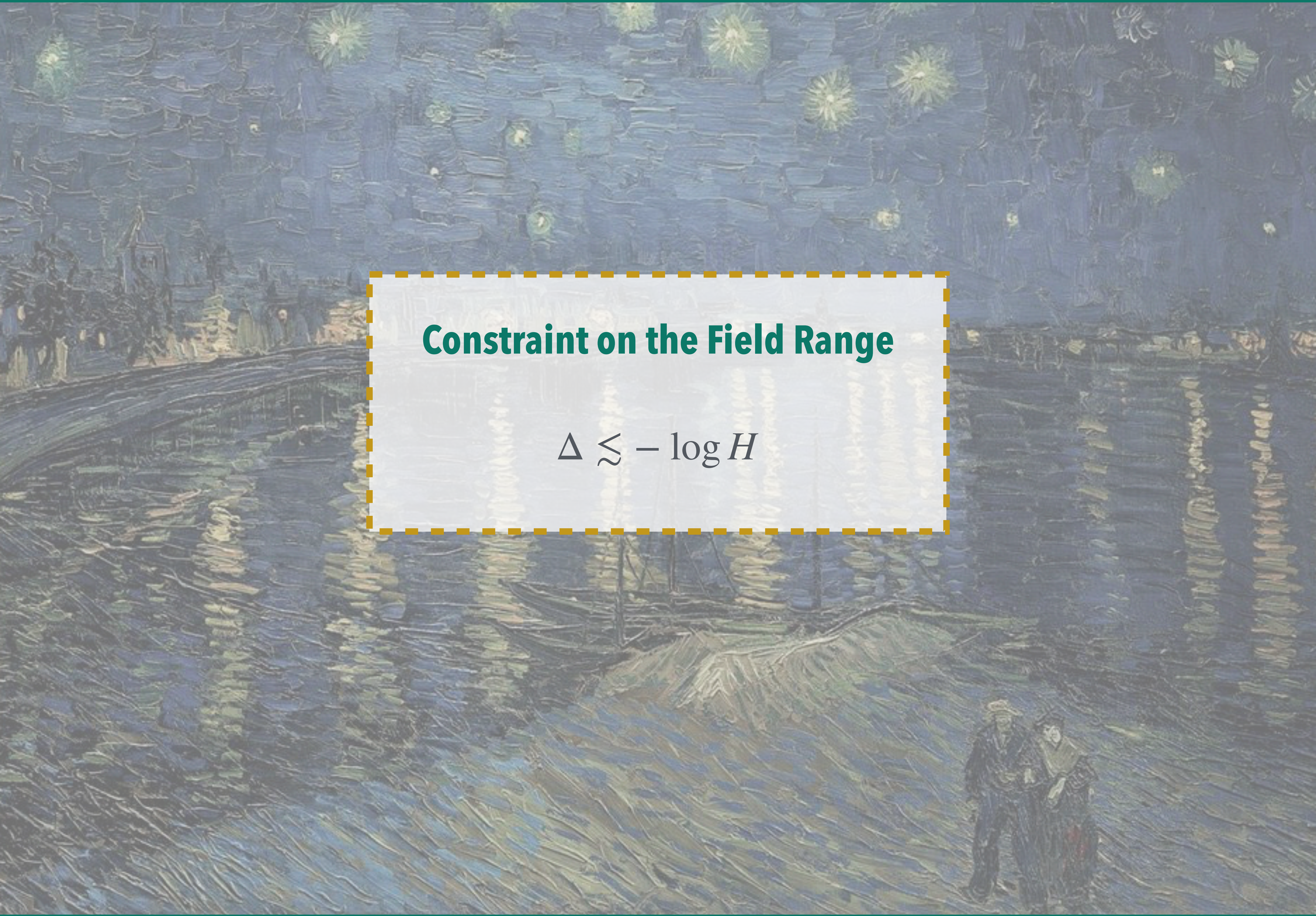
See **Terada**'s talk on **Thursday** about GC's constraint on inflationary models!



Constraint on the Field Range

$$\Delta \lesssim -\log H$$

Universal upper bound

MS, Valenzuela 2018

$$H < \Lambda_{QG} \leq M_{\mathrm{P}}\, e^{-\gamma\Delta}$$

consistency of EFT

implication of the SDC

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consistency of EFT

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upper bound on field displacement

$$\boxed{\Delta < \frac{1}{\lambda} \log \frac{M_{\mathrm{P}}}{H}}$$

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$$\Delta \lesssim 140\ M_\text{P}$$

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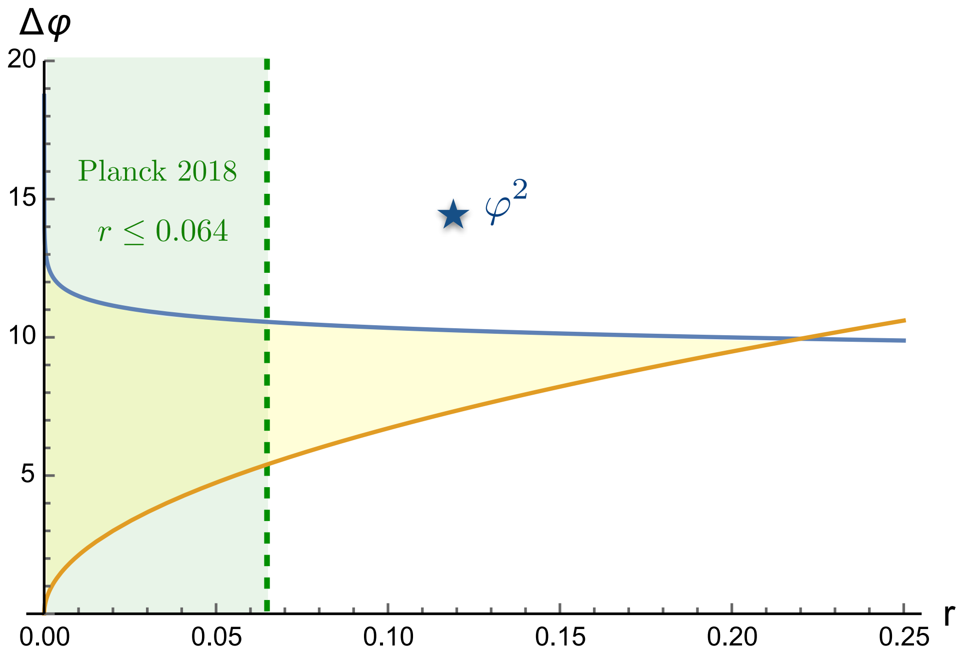
inflation

$$\Delta < \frac{1}{2\lambda}\left(\log \frac{\pi^2 A_s}{2} + \log r\right)$$



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$$\Delta \lesssim 140\ M_{\mathrm{P}}$$

Universal upper bound

MS, Valenzuela 2018

see also

Etheredge, Heidenreich, Kaya, Qiu, Rudelius 2022

van de Heisteeg, Vafa, Wiesner, Wu 2023

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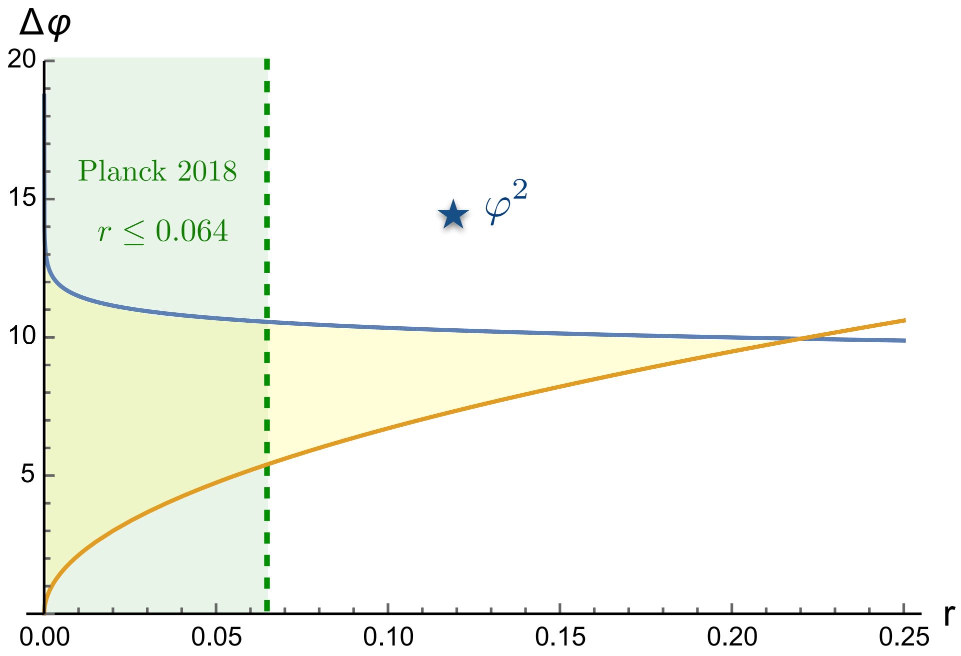

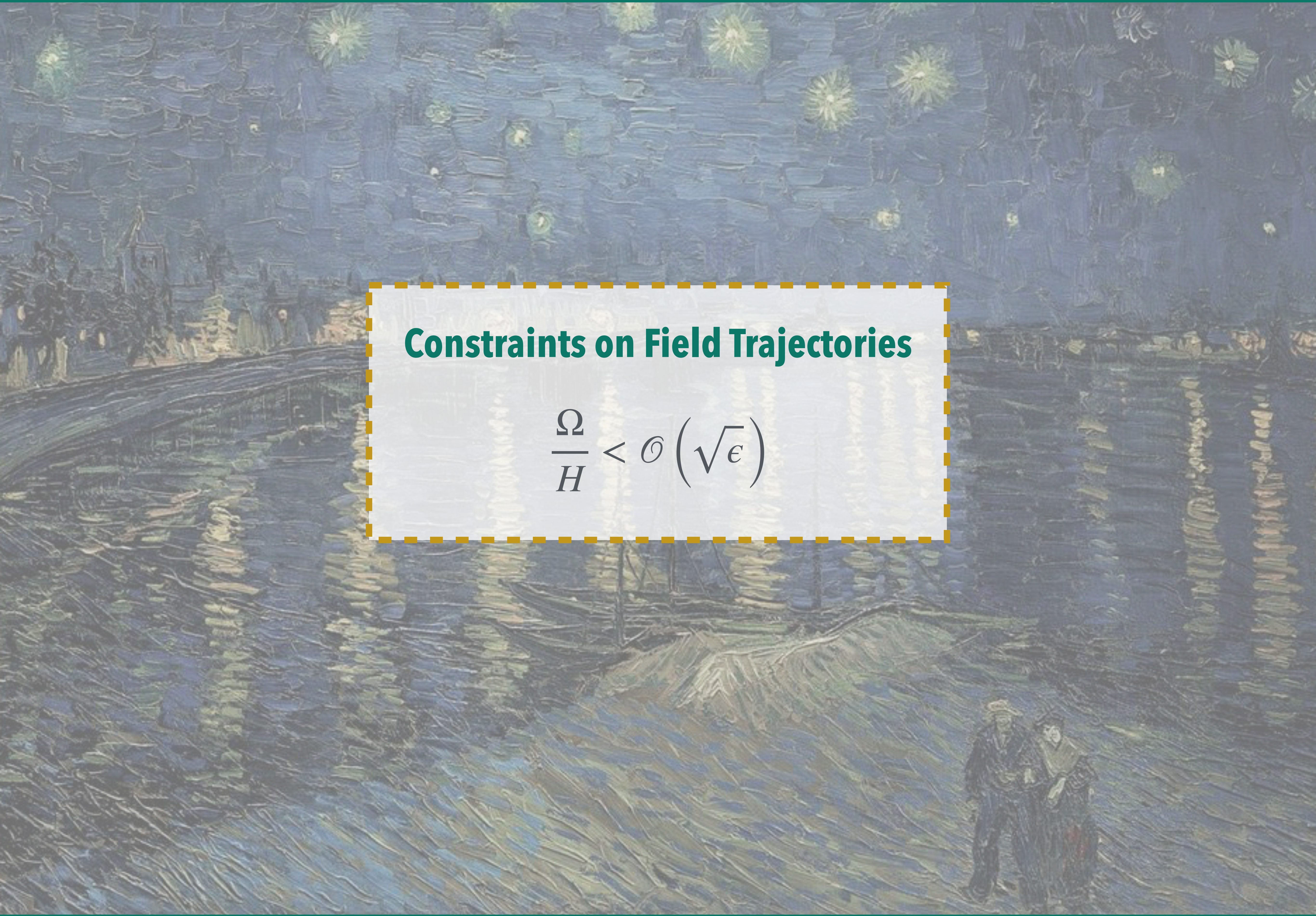

Constraints on Field Trajectories

$$\frac{\Omega}{H} < \mathcal{O}\left(\sqrt{\epsilon}\right)$$

Decay rate of the SDC

Calderòn-Infante, Uranga, Valenzuela 2020

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$$\lambda(\Delta) = -\frac{d\log m}{d\Delta} = -T^i\partial_i \log m$$

T^i = normalized tangent vector

$\partial_i \log m$ = gradient of the tower mass

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if the gradient of the mass is aligned along geodesics (most of string theory examples)

$$\lambda = -|\partial \log m| \cos\theta = \lambda_g \cos\theta$$

θ = angle between the trajectory and the geodesic

λ_g = decay rate for geodesics= highest value of λ

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Andriot, Cribiori, Erkinger 2020
Glender, Valenzuela 2020
Castellano et al 2021
Etheredge et al 2022

$$\lambda \geq \lambda_0$$

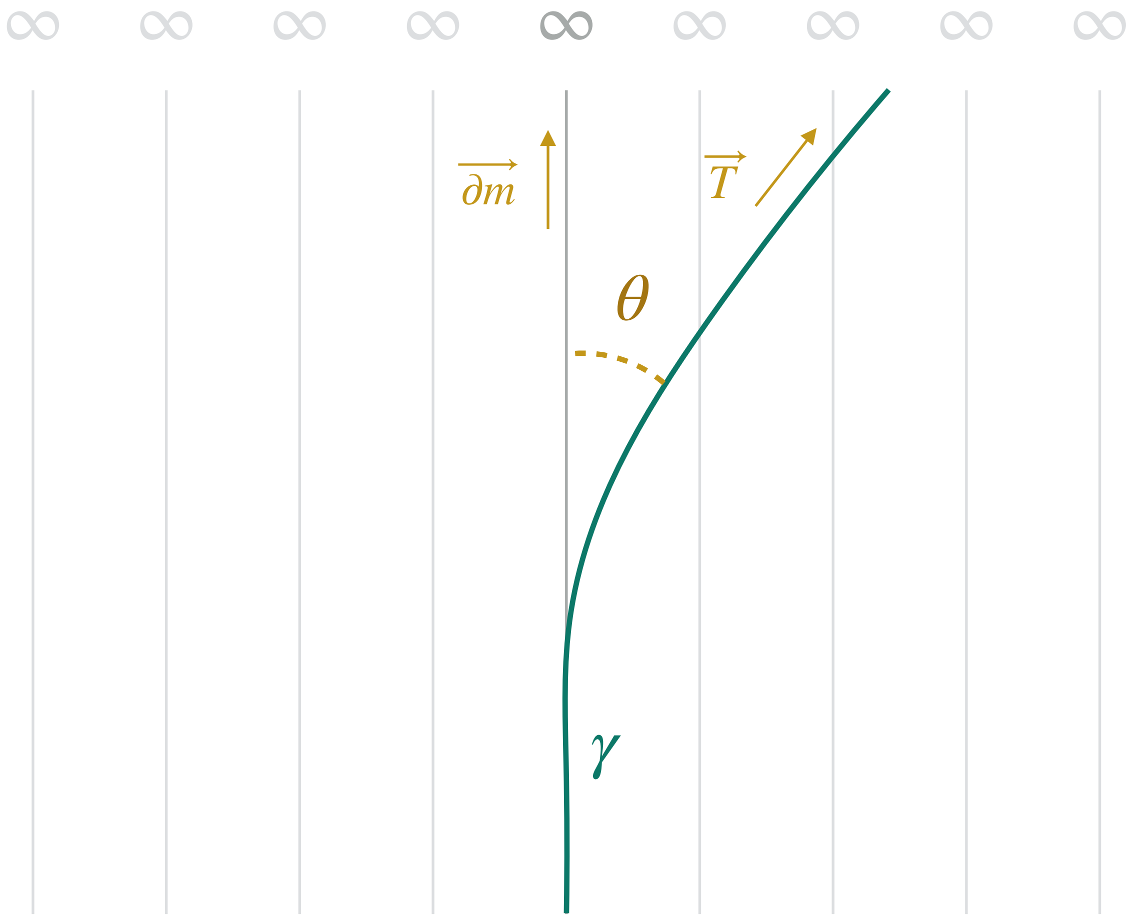
LOWER BOUND

$$\longrightarrow$$

$$\cos\theta \geq -\frac{\lambda_0}{|\partial \log m|} = \frac{\lambda_0}{\lambda_g}$$

MAXIMUM DEVIATION ANGLE

Decay rate of the SDC



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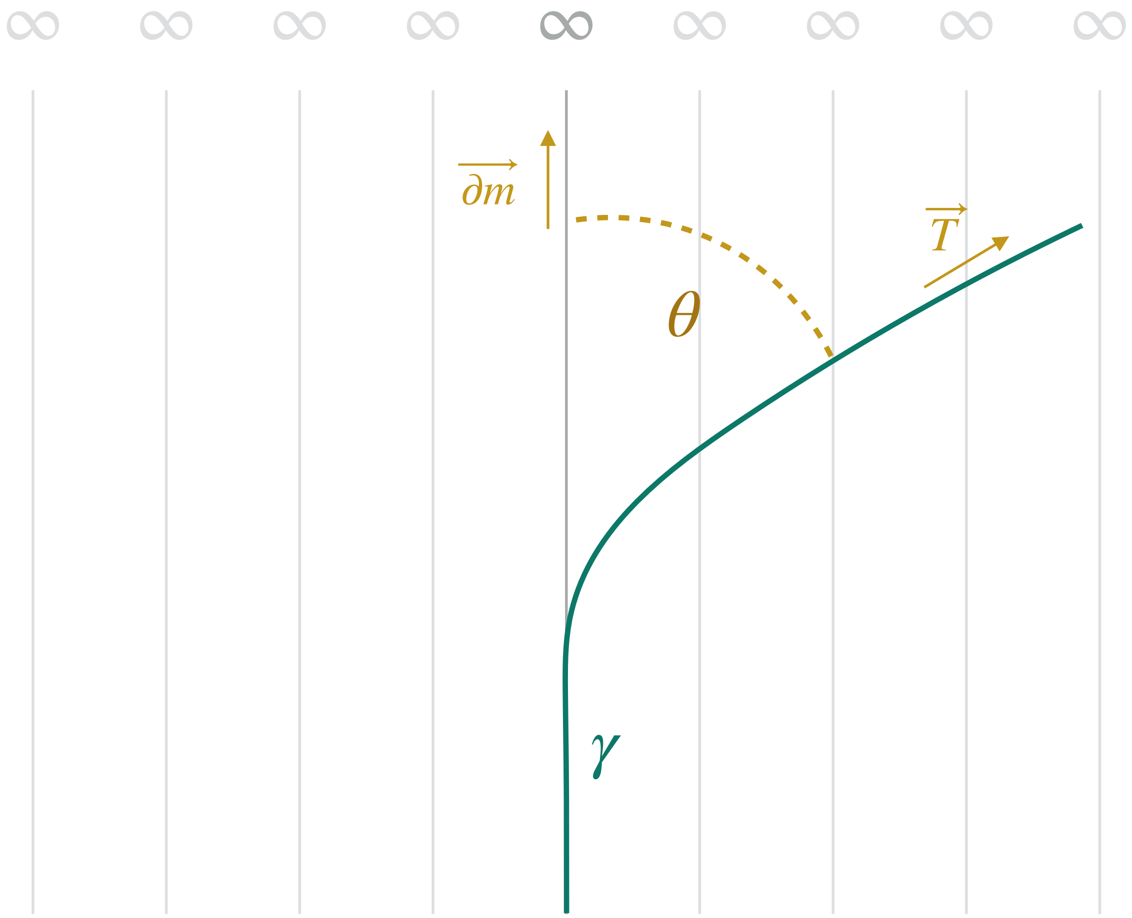

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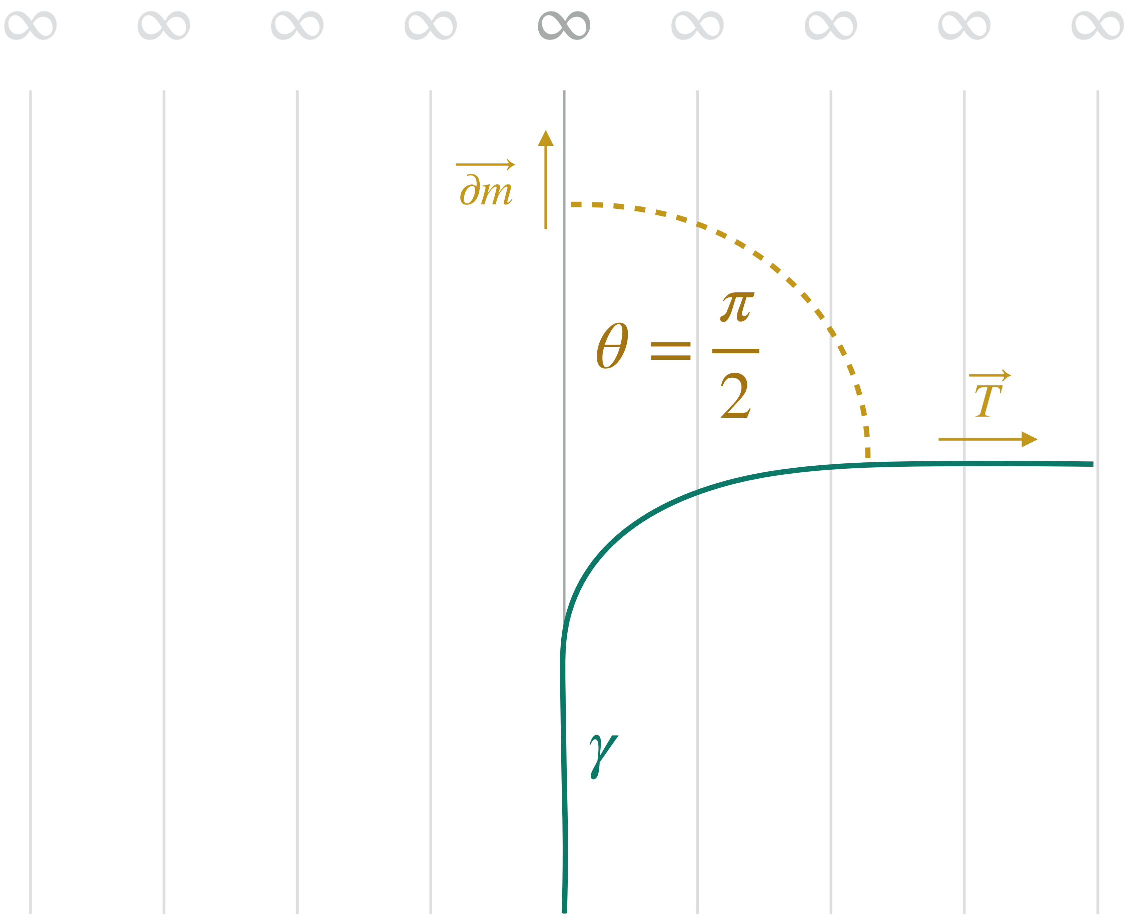

$\lambda = 0$

⚠

Andriot, Cribiori, Erkinger 2020
Glender, Valenzuela 2020
Castellano et al 2021
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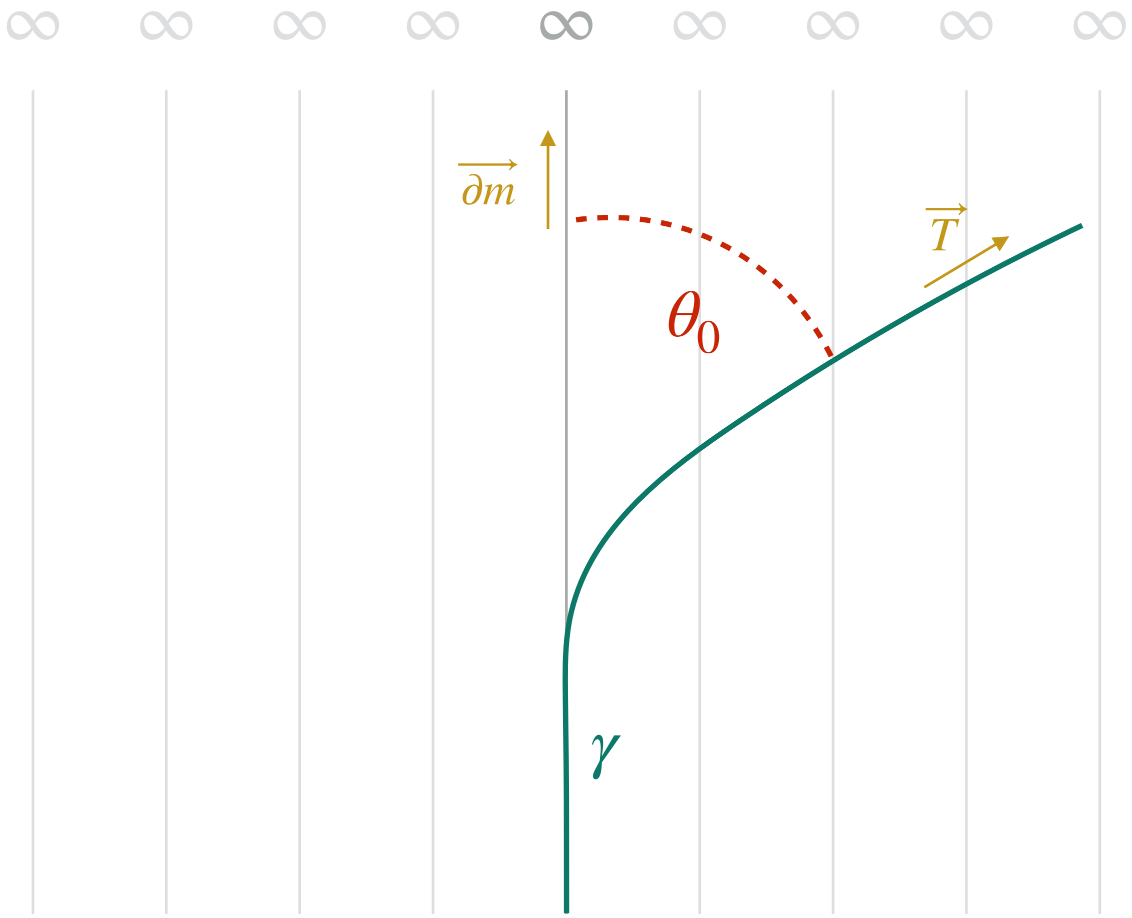

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MAXIMUM DEVIATION ANGLE

Multi-field setup and **trajectories** in moduli space

Freigang, Lüst, Nian, MS 2023

- Scalar fields in **Minkowski space time**

$$\mathscr{L} = -\frac{1}{2}\eta^{\mu\nu}G_{ab}\,\partial_\mu\Phi^a\partial_\nu\Phi^b$$

$$\Big\downarrow$$

$$\boxed{\ddot{\Phi}^a + \Gamma^a_{bc}\dot{\Phi}^b\dot{\Phi}^c = 0}$$

EoM = geodesic equation

scalar fields will move along geodesics

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$$D_tA^a \equiv \dot{A}^a + \Gamma^a_{bc}A^b\dot{\Phi}^c$$

covariant derivative

$$\boxed{D_t\dot{\Phi}^a = 0}$$

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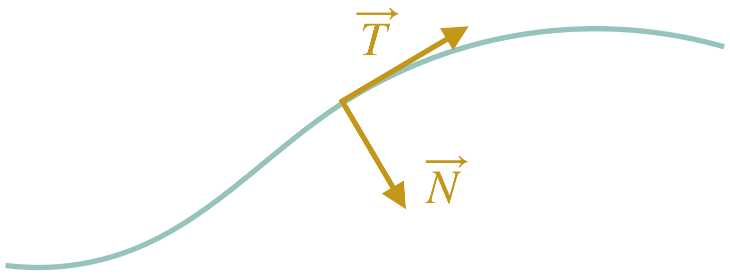

$$T^a = \frac{\dot{\Phi}^a}{\dot{\Phi}}$$

tangent vector

$$N^a = -\frac{D_tT^a}{|D_tT|}$$

normal vector

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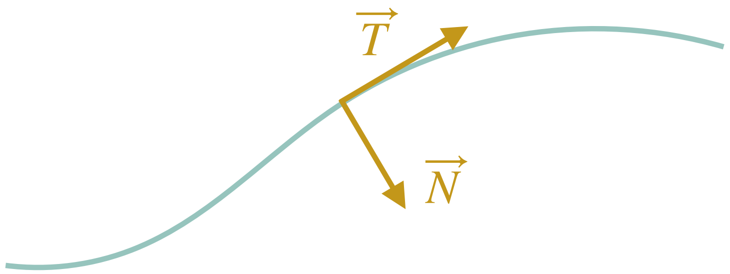

$$T^a = \frac{\dot{\Phi}^a}{\dot{\Phi}}$$

tangent vector

$$N^a = -\frac{D_tT^a}{|D_tT|}$$

normal vector

$$\dot{\Phi} = \sqrt{G_{ab}\dot{\Phi}^a\dot{\Phi}^b}$$

speed

$$\Omega = |D_tT|$$

turning rate

$$\ddot{\Phi} = 0$$

tangent projection

$$\Omega\dot{\Phi} = 0$$

normal projection

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Freigang, Lüst, Nian, MS 2023

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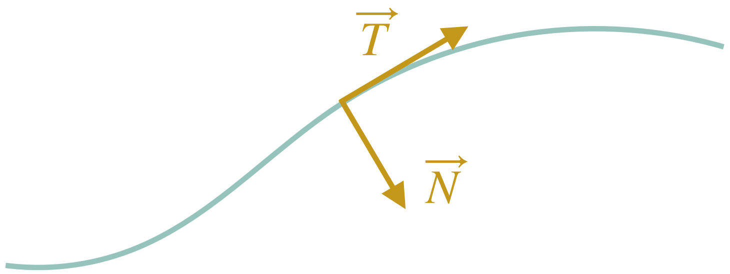

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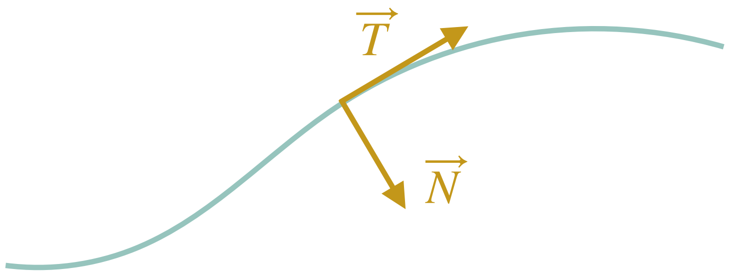
Multi-field setup and **trajectories** in moduli space

Freigang, Lüst, Nian, MS 2023

- Scalar fields with potential in **Minkowski space time**

$$\mathscr{L} = -\frac{1}{2}\eta^{\mu\nu}G_{ab}\,\partial_\mu\Phi^a\partial_\nu\Phi^b - V(\Phi^a)$$



$$\ddot{\Phi} + V_T = 0 \qquad \Omega\dot{\Phi} = V_N$$

$$V_T \equiv T^a V_a \qquad V_N \equiv N^a V_a$$

Multi-field setup and **trajectories** in moduli space

Freigang, Lüst, Nian, MS 2023

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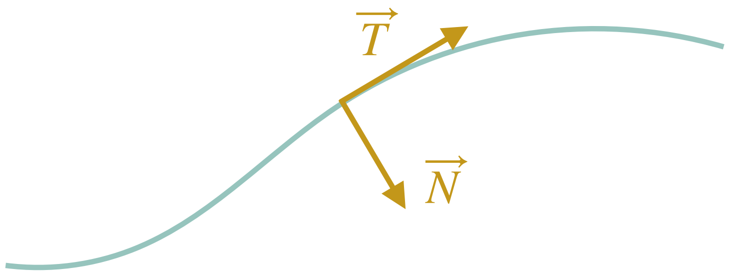

$$\mathscr{L} = -\frac{1}{2}\eta^{\mu\nu}G_{ab}\,\partial_\mu\Phi^a\partial_\nu\Phi^b - V(\Phi^a)$$

$$\ddot{\Phi} + V_T = 0 \qquad \Omega\dot{\Phi} = V_N$$

$$V_T \equiv T^a V_a \qquad V_N \equiv N^a V_a$$

- Scalar fields with potential in **FLRW space time**

$$\mathscr{L} = \frac{1}{2}R - \frac{1}{2}g^{\mu\nu}G_{ab}\partial_\mu\Phi^a\partial_\nu\Phi^b - V(\Phi^a)$$

$$\ddot{\Phi} + 3H\dot{\Phi} + V_T = 0 \qquad \Omega\dot{\Phi} = V_N$$

Multi-field cosmic acceleration

Achucarro, Palma 2018
Freigang, Lüst, Nian, MS 2023

$$3H^2 - \frac{1}{2}\dot{\Phi}^2 - V = 0 \qquad \ddot{\Phi} + 3H\dot{\Phi} + V_T = 0 \qquad \Omega\dot{\Phi} = V_N$$

Multi-field cosmic acceleration

Achucarro, Palma 2018
Freigang, Lüst, Nian, MS 2023

$$3H^2 - \frac{1}{2}\dot{\Phi}^2 - V = 0 \qquad \ddot{\Phi} + 3H\dot{\Phi} + V_T = 0 \qquad \Omega\dot{\Phi} = V_N$$

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\Phi}^2}{2H^2}$$

acceleration parameter

$$\eta \equiv \frac{\dot{\epsilon}}{H\epsilon} = 2\epsilon + 2\frac{\ddot{\Phi}}{H\dot{\Phi}}$$

eta parameter

Multi-field cosmic acceleration

Achucarro, Palma 2018
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eta parameter

$$\frac{|\nabla V|^2}{V^2} = 2\epsilon\left(\left(1 + \frac{\eta}{2(3-\epsilon)}\right)^2 + \frac{\Omega^2}{H^2(3-\epsilon)^2}\right)$$

Multi-field cosmic acceleration

Achucarro, Palma 2018
Freigang, Lüst, Nian, MS 2023

$$3H^2 - \frac{1}{2}\dot{\Phi}^2 - V = 0 \qquad \ddot{\Phi} + 3H\dot{\Phi} + V_T = 0 \qquad \Omega\dot{\Phi} = V_N$$

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\Phi}^2}{2H^2}$$ *acceleration parameter*

$$\eta \equiv \frac{\dot{\epsilon}}{H\epsilon} = 2\epsilon + 2\frac{\ddot{\Phi}}{H\dot{\Phi}}$$ *eta parameter*

$$\frac{|\nabla V|^2}{V^2} = 2\epsilon\left(\left(1 + \frac{\eta}{2(3-\epsilon)}\right)^2 + \frac{\Omega^2}{H^2(3-\epsilon)^2}\right)$$

$\epsilon < 1$

$$\frac{|\nabla V|^2}{V^2} \simeq 2\epsilon\left(\left(1 + \frac{\eta}{6}\right)^2 + \frac{\Omega^2}{9H^2}\right)$$

Example: **scaling cosmologies** see talks by **Shiu** and **Tonioni**

Multi-field cosmic acceleration

Achucarro, Palma 2018
Freigang, Lüst, Nian, MS 2023

$$3H^2 - \frac{1}{2}\dot{\Phi}^2 - V = 0 \qquad \ddot{\Phi} + 3H\dot{\Phi} + V_T = 0 \qquad \Omega\dot{\Phi} = V_N$$

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\Phi}^2}{2H^2}$$ *acceleration parameter*

$$\eta \equiv \frac{\dot{\epsilon}}{H\epsilon} = 2\epsilon + 2\frac{\ddot{\Phi}}{H\dot{\Phi}}$$ *eta parameter*

$$\frac{|\nabla V|^2}{V^2} = 2\epsilon\left(\left(1+\frac{\eta}{2(3-\epsilon)}\right)^2 + \frac{\Omega^2}{H^2(3-\epsilon)^2}\right)$$

$\epsilon < 1$

$$\frac{|\nabla V|^2}{V^2} \simeq 2\epsilon\left(\left(1+\frac{\eta}{6}\right)^2 + \frac{\Omega^2}{9H^2}\right)$$

$\eta, \epsilon \ll 1$ *slow roll*

$$\frac{|\nabla V|^2}{V^2} \simeq 2\epsilon\left(1+\frac{\Omega^2}{9H^2}\right)$$

Example: **scaling cosmologies**

see talks by **Shiu** and **Tonioni**

Asymptotic acceleration and **bound on the turning rate**

Freigang, Lüst, Nian, MS 2023

- **1 hyperbolic plane**

$$\mathrm{d}\Delta^2 = G_{ab}\,\mathrm{d}\Phi^a\mathrm{d}\Phi^b = \frac{n^2}{s^2}\left(\mathrm{d}s^2 + \mathrm{d}\phi^2\right)$$

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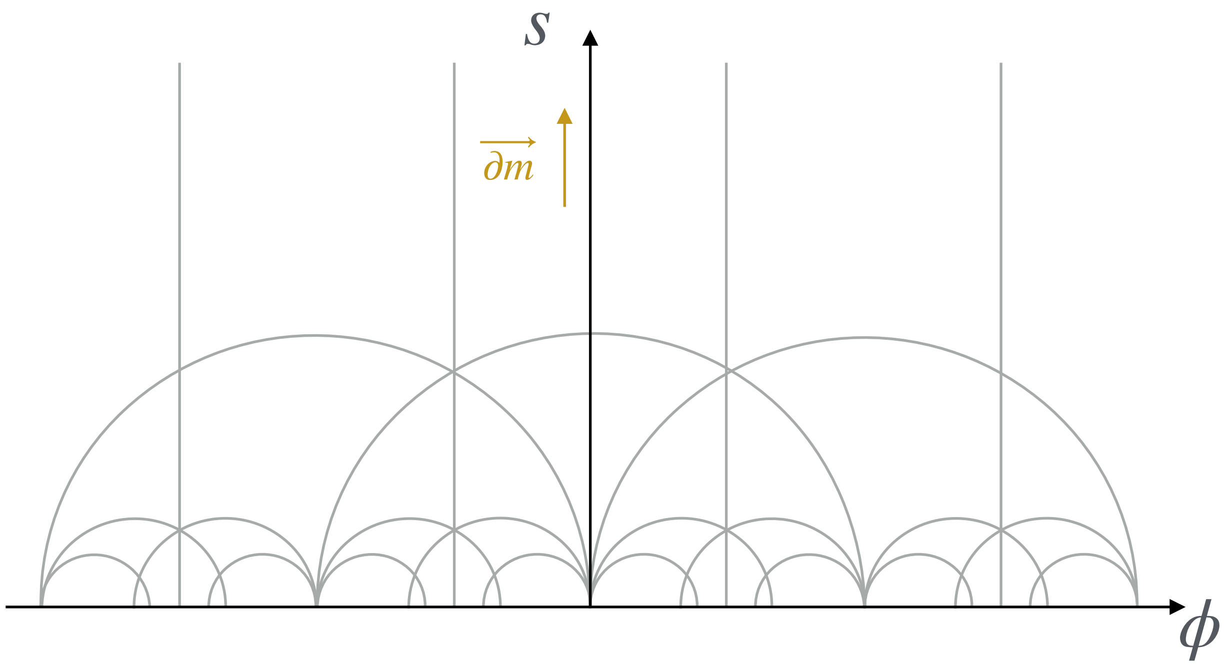

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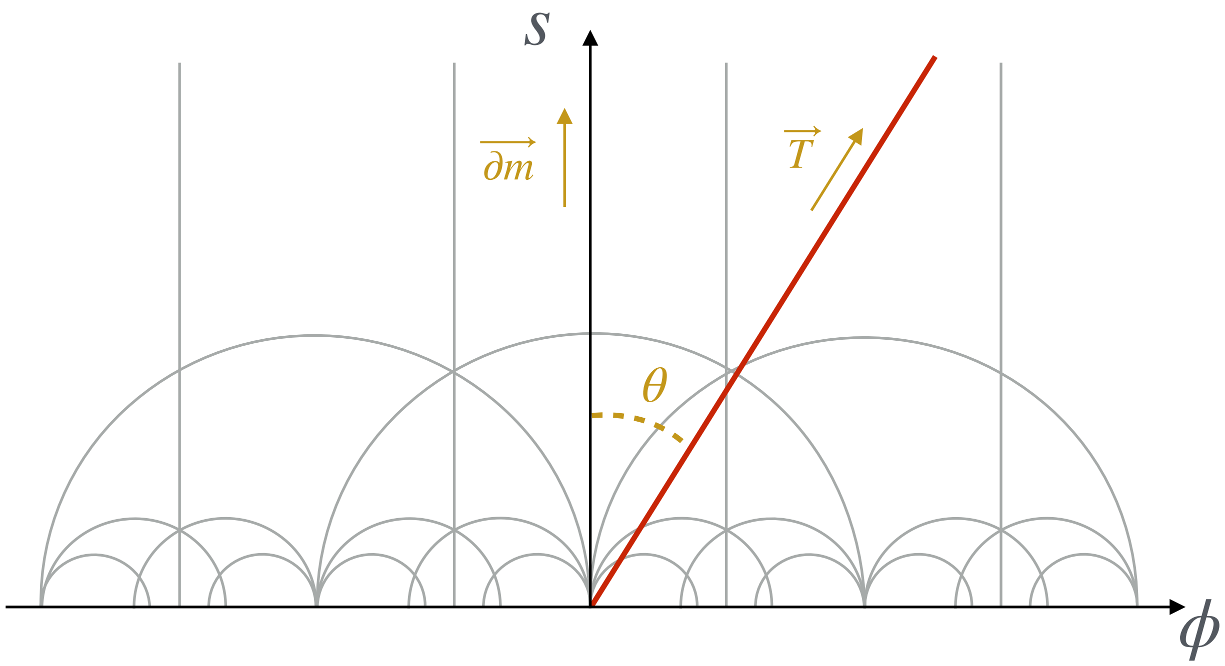
trajectory



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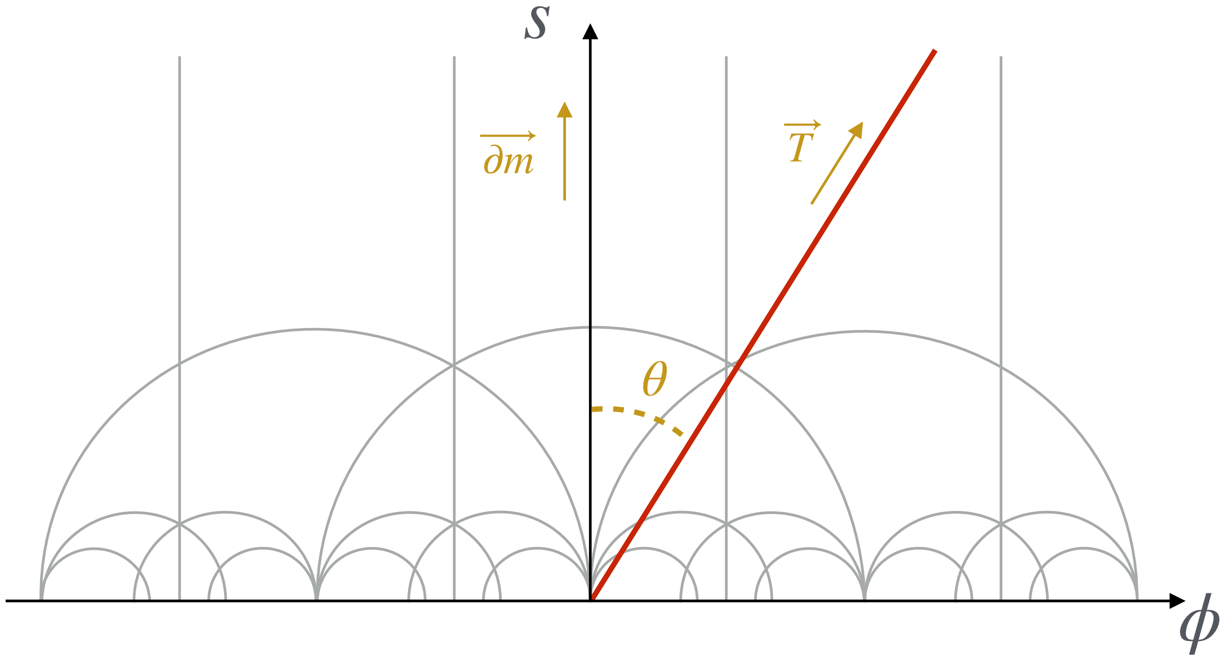

$$\Omega = \frac{n}{s}\sqrt{(D_t T^s)^2 + (D_t T^\phi)^2} = \frac{|\sin\theta|}{n}\dot{\Phi}$$

$$\xrightarrow{\dot{\Phi}^2 = 2\epsilon H^2}$$

$$\boxed{\frac{\Omega}{H} = \frac{|\sin\theta|}{n}\sqrt{2\epsilon}}$$

↑

large curvature?

Aragam, Chiovoloni, Paban, Rosati. Zavala 2021

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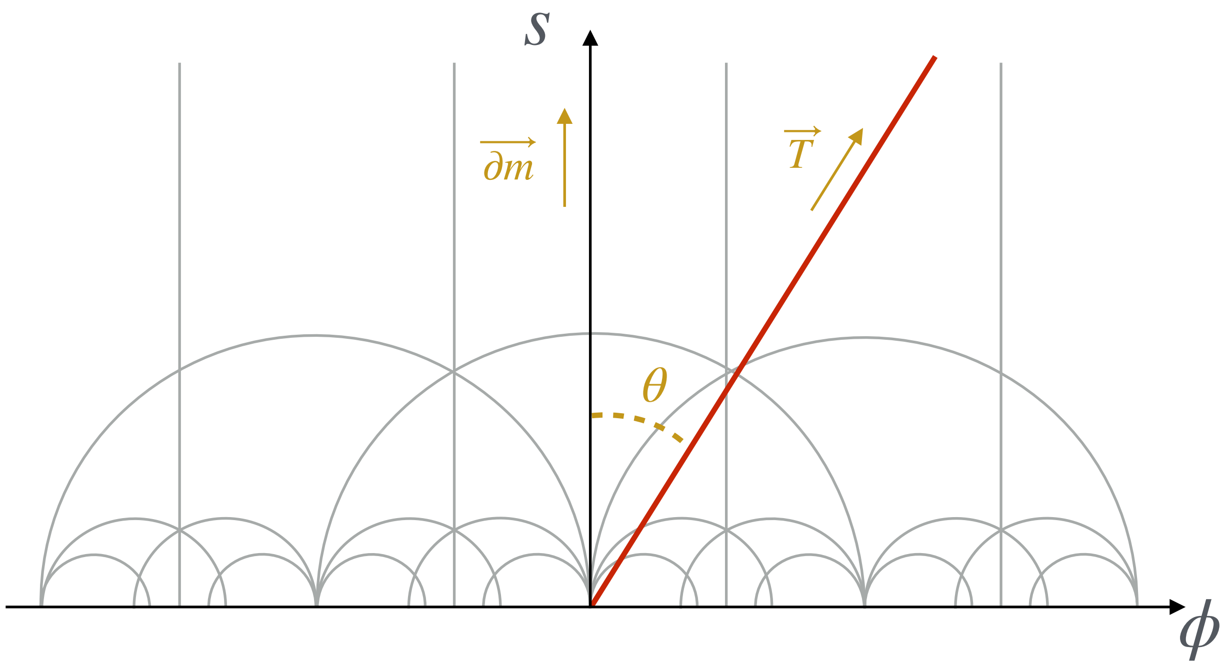

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$$\frac{\Omega}{H} = F(\theta, R)\sqrt{\epsilon} \qquad F(\theta, R) = |\sin\theta|\sqrt{-R} \qquad F < |\sin\theta_0|\sqrt{-R}$$

Asymptotic acceleration and **bound on the turning rate**

Freigang, Lüst, Nian, MS 2023

- Product of **2 hyperbolic planes**

$$\mathrm{d}\Delta^2 = \frac{n^2}{s^2}\left(\mathrm{d}s^2 + \mathrm{d}\phi^2\right) + \frac{m^2}{u^2}\left(\mathrm{d}u^2 + \mathrm{d}\psi^2\right)$$

- Product of **N hyperbolic planes**

$$\mathrm{d}\Delta^2 = \sum_{i=1}^{N} \frac{n_i^2}{s_i^2}\left(\mathrm{d}s_i^2 + \mathrm{d}\phi_i^2\right)$$

see
Guoen **Nian**'s parallel talk
on **Thursday**!

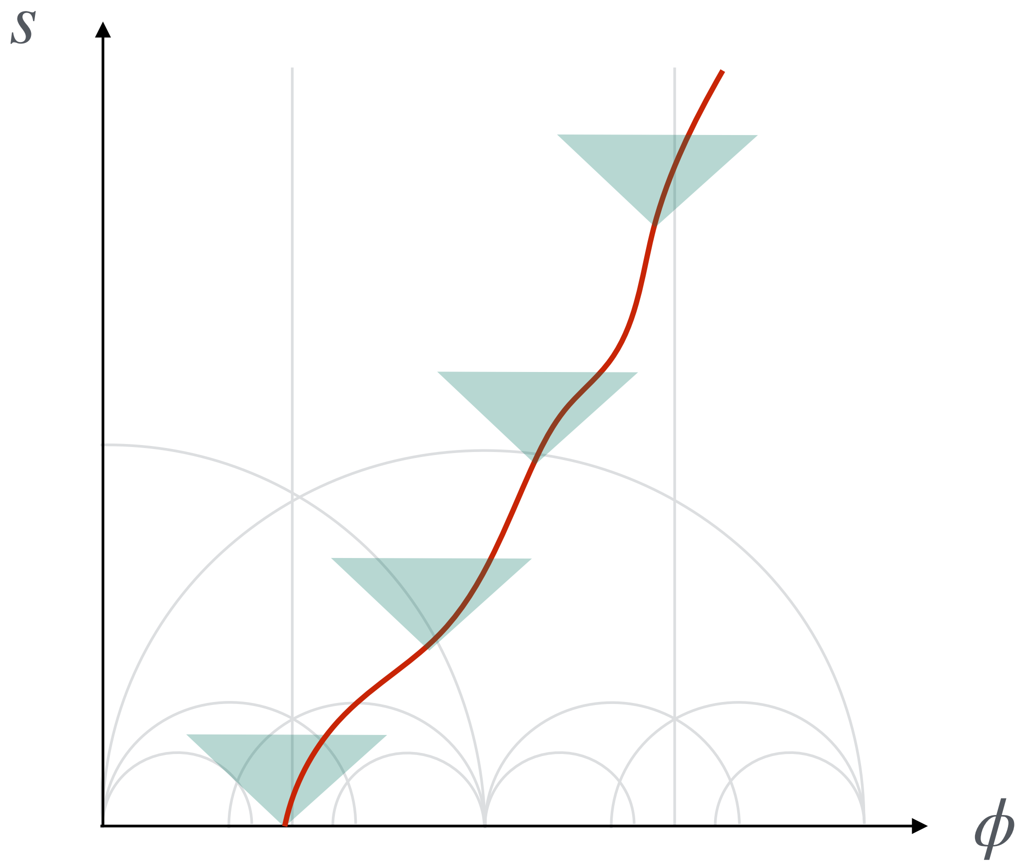
Moving away from the boundary of moduli space

Freigang, Lüst, Nian, MS 2023

- **Time-dependent deviation angle**

$$\boxed{\frac{\mathrm{d}\phi}{\mathrm{d}s} = \beta(t) = \tan\theta(t)}$$

trajectory



$$\theta(s) \leq \theta_0 \quad \leftarrow\!\!-\!\!-\!\!\rightarrow \quad \lambda(s) \geq \lambda_0$$

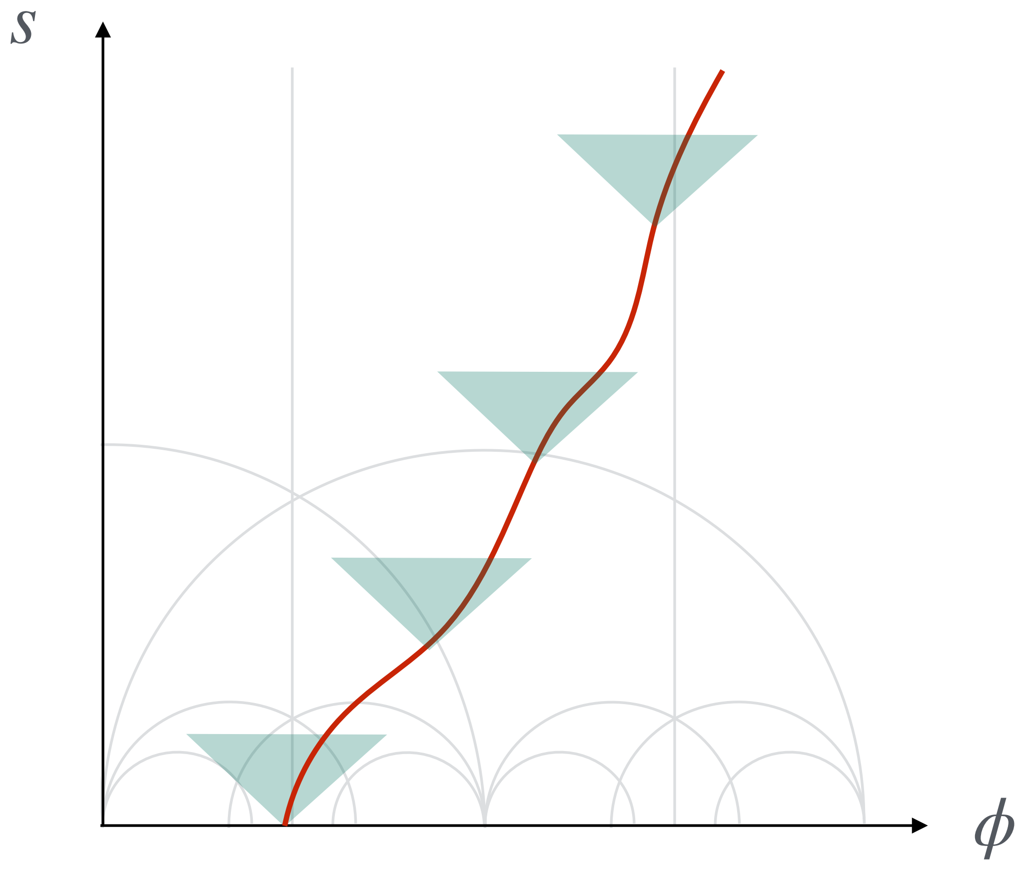
Moving away from the boundary of moduli space

Freigang, Lüst, Nian, MS 2023

- **Time-dependent deviation angle**

$$m = m_0 \exp(-\lambda\Delta) + \delta m(\Delta)$$ *tower mass*

$$\frac{\mathrm{d}\phi}{\mathrm{d}s} = \beta(t) = \tan\theta(t)$$ *trajectory*



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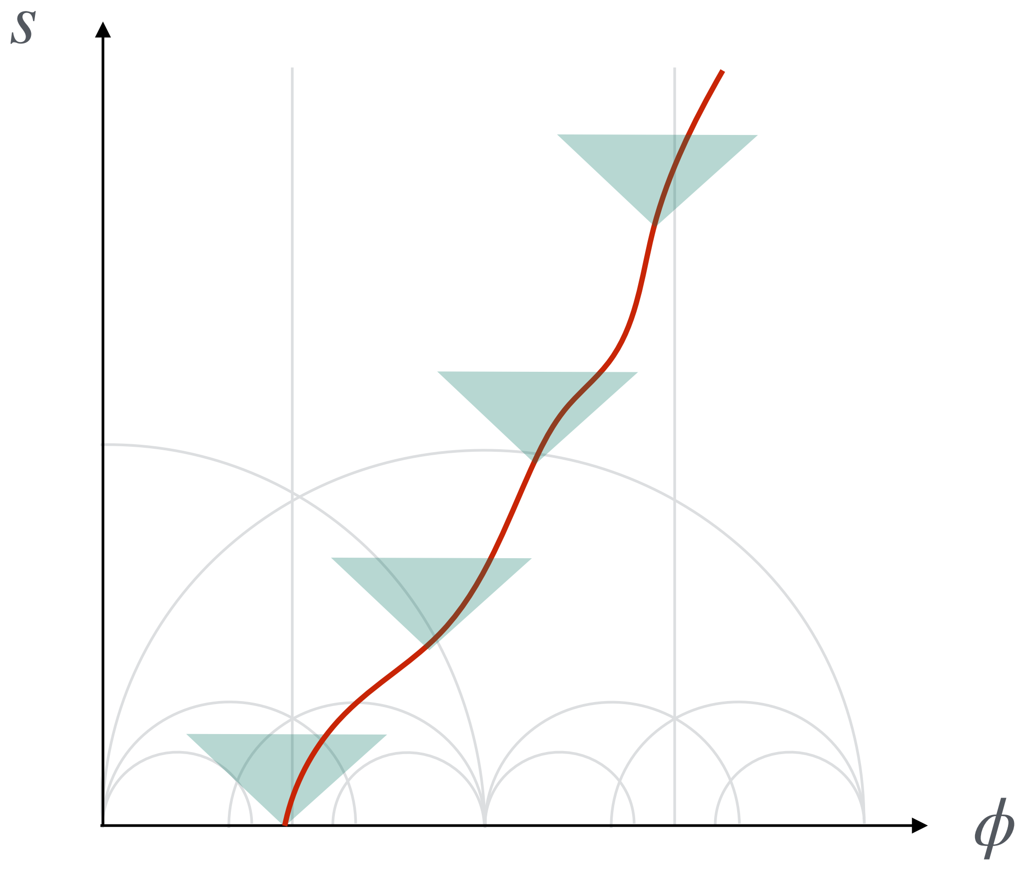
tower mass

$$\Omega = \left|\frac{\sin\theta}{n}\dot{\Phi} - \dot{\theta}\right|$$

turning rate

how big can $\dot{\theta}$ be?



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$$\theta(s) = \theta_\infty + \sum_{n>0} \frac{c_n}{s^n}$$

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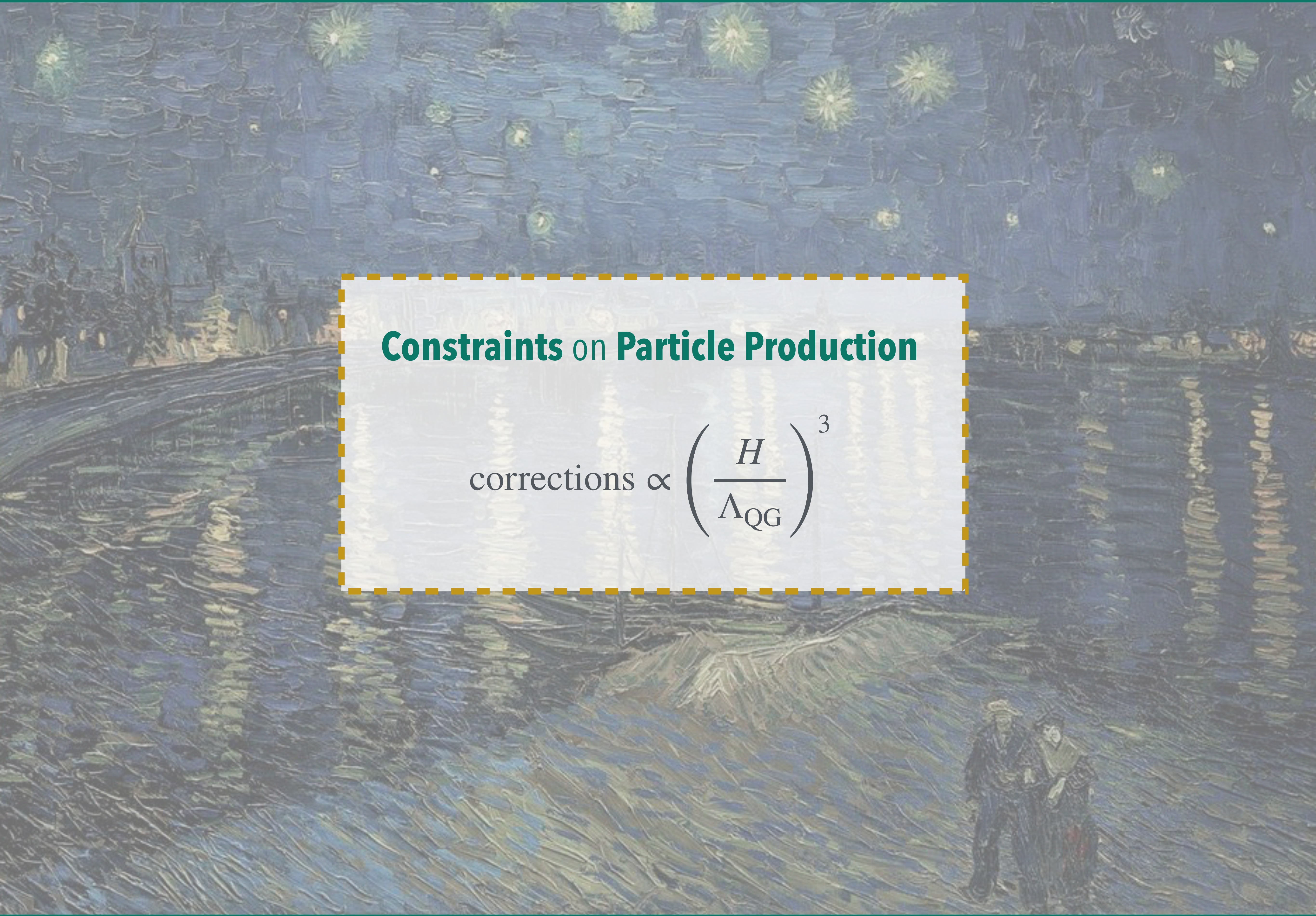
- **Asymptotic expansion of θ**

$$\theta(s) = \theta_\infty + \sum_{n>0} \frac{c_n}{s^n} \dashrightarrow \boxed{\left| \frac{\dot{\theta}(s)}{H} \right| \leq 2\sqrt{2}\, \frac{k}{n}\, \theta_0 \sqrt{\epsilon}}$$

$\dot{\Phi}^2 = 2\epsilon H^2$

$$\frac{\Omega}{H} \simeq \sqrt{\epsilon}$$



Constraints on **Particle Production**

$$\text{corrections} \propto \left(\frac{H}{\Lambda_{\mathrm{QG}}}\right)^3$$

SDC and **particle production**

coupling between **inflaton** and other **fields** → production **of quanta** → **injection of energy** = **additional friction** → **change** of **observable predictions**

SDC and **particle production**

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- **Inflaton-gauge** fields coupling *Anber, Sorbo 2010*

$$\mathscr{L} = -\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - \varphi\ F\tilde{F}$$

- **Inflaton-scalar** fields coupling *Green, Horn, Senatore, Silverstein 2009* *“Trapped inflation”*

$$\mathscr{L} = -\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - \frac{1}{2}\sum_n \left[(\partial\chi_n)^2 - g^2(\varphi - \varphi_{0n})^2\chi_n^2\right]$$

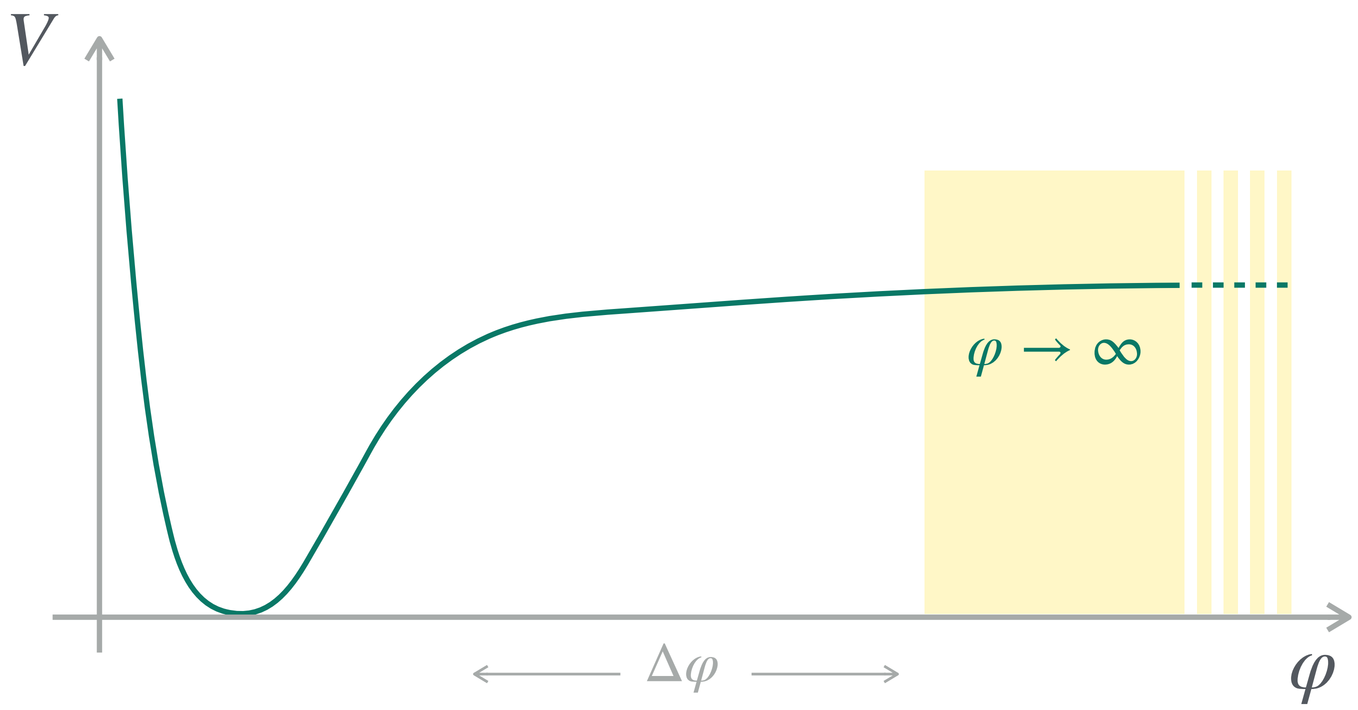
SDC and **particle production**

Lüst, Masias, Pieroni, Scalisi - work in progress

$$\mathscr{L} = -\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - \frac{1}{2}\sum_i \left[(\partial\chi_i)^2 - m_n^2 e^{-2\lambda\varphi}\chi_n^2\right]$$

mass of the SDC tower

$$m \sim e^{-\lambda\varphi}$$



SDC and **particle production**

Lüst, Masias, Pieroni, Scalisi - work in progress

- **Scalar power spectrum**

$$P_\zeta(k) = P_\zeta^h + P_\zeta^s = \frac{H^4}{(2\pi)^2\ \dot{\varphi}_0^2}\left(1 + 0.0025\ \frac{H^3}{\Lambda_{QG}^3}\lambda^2\right)$$

⚠

EFT reasoning
would suggest first
correction as $\Lambda_{IR}/\Lambda_{UV}$

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for $H < \Lambda_{QG}$

and $\lambda = \mathcal{O}(1)$

$$P^h_\zeta > P^s_\zeta$$

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for $H \sim \Lambda_{QG}$
and $\lambda > 20$ ⚠

$$P_\zeta^h \sim P_\zeta^s$$

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for $H \sim \Lambda_{QG}$
and $\lambda > 20$

$$P_\zeta^h \sim P_\zeta^s$$

Corrections disappears
when tower decouples

$\Lambda_{QG} \to \infty \qquad (m_n \to \infty)$

or

$\lambda \to 0$

SDC and **particle production**

Lüst, Masias, Pieroni, Scalisi - work in progress

- **Non Gaussianities**

$$f_{NL,equil} \simeq 0.0007\frac{\lambda\dot{\varphi}}{H}(\lambda M_{\rm P})^2\left[1+0.0025(\lambda M_{\rm P})^2\left(\frac{H}{\Lambda_{\rm QG}}\right)^3\right]^{-2}\left(\frac{H}{\Lambda_{\rm QG}}\right)^3$$

- **Tensor-to-scalar ratio**

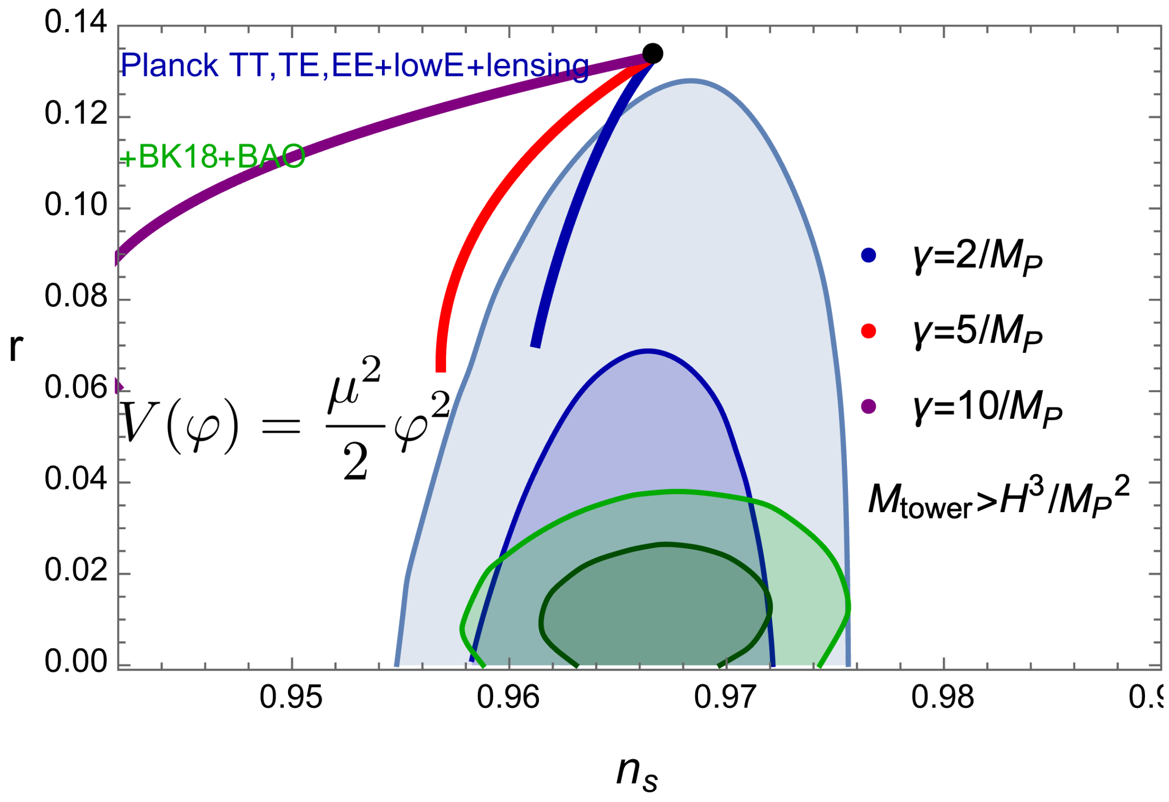
$$r = 9.2\cdot 10^7\frac{H^2}{M_{\rm P}^2}\left[1+0.17\left(\frac{H}{\Lambda_{\rm QG}}\right)^3\right]$$

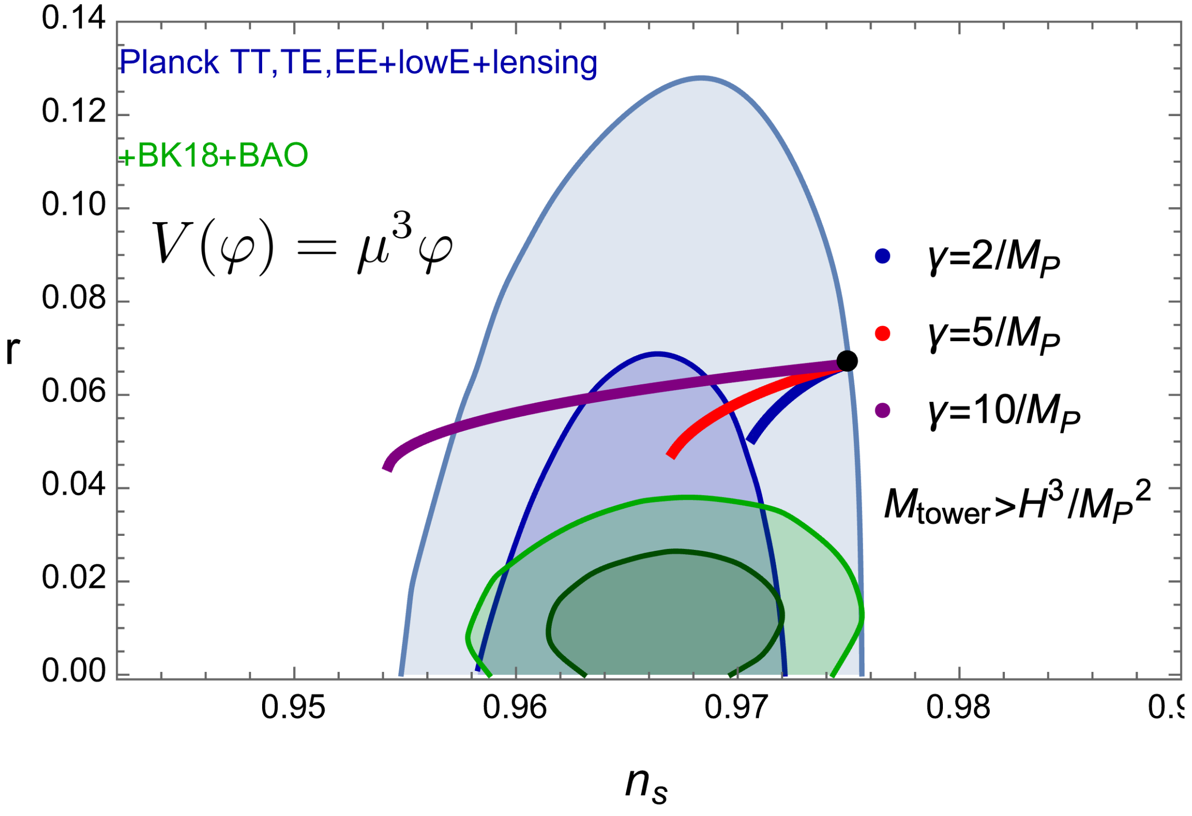
- **Scalar spectral tilt**

$$n_s - 1 = (-2\epsilon-\eta)\left[1-\left(\frac{\gamma M_{\rm P}}{20}\right)^2\left(\frac{H}{\Lambda_{QG}}\right)^3\right] - \left(5\epsilon+\sqrt{2\epsilon}\gamma M_{\rm P}\right)\left(\frac{\gamma M_{\rm P}}{20}\right)^2\left(\frac{H}{\Lambda_{QG}}\right)^3$$

SDC and **particle production**

Lüst, Masias, Pieroni, Scalisi - work in progress





Conclusions

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Universal **upper bound**
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$$\Delta \lesssim -\log H$$

MS, Valenzuela 2018
MS 2019

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Upper bound on the **turning rate**

$$\frac{\Omega}{H} < \mathcal{O}\left(\sqrt{\epsilon}\right)$$

Trajectories mainly geodesic

Freigang, Lüst, Nian, MS 2023

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Particle production very constrained by SDC but still **observable effects** of order

$$\left(H/\Lambda_{\mathrm{QG}}\right)^{3}$$

Lüst, Masias, Pieroni, MS - in progress

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thanks!

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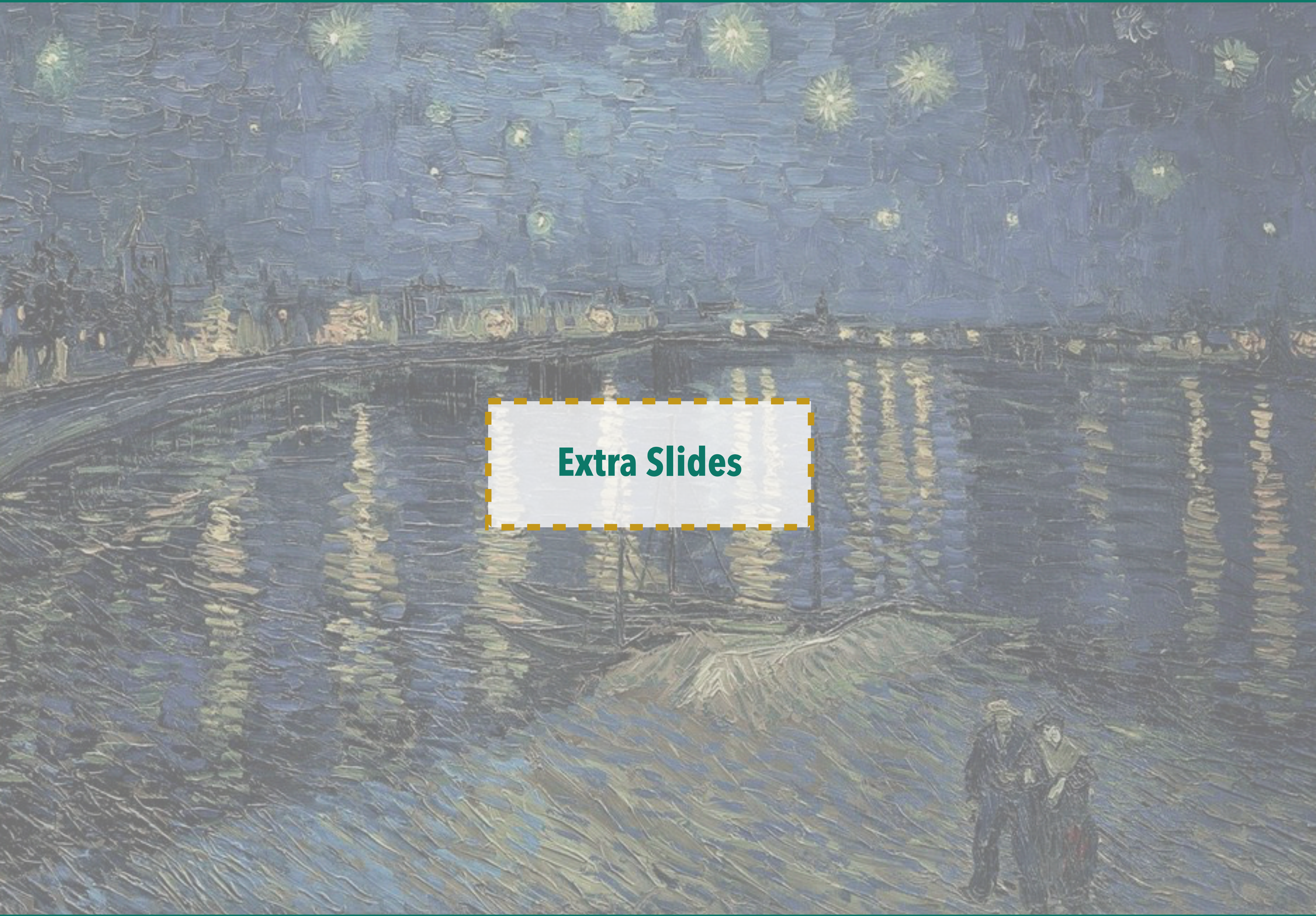

Extra Slides

Universal upper bound

MS 2019

SDC

$$m \sim m_0 e^{-\lambda\Delta}$$

+

Higuchi bound

$$m^2 > s(s-1)H^2$$

$$\boxed{\Delta \leq \frac{1}{\lambda}\left[\frac{m_0}{H}\frac{1}{\sqrt{s(s-1)}}\right]}$$

one-to-one correspondence between a ***single* HS state** and a **specific maximum value for the inflaton range**

infinite tower of all spins incompatible with inflation ⚠

Asymptotic acceleration and **bound on the turning rate**

Freigang, Lüst, Nian, MS 2023

- **1 hyperbolic plane**

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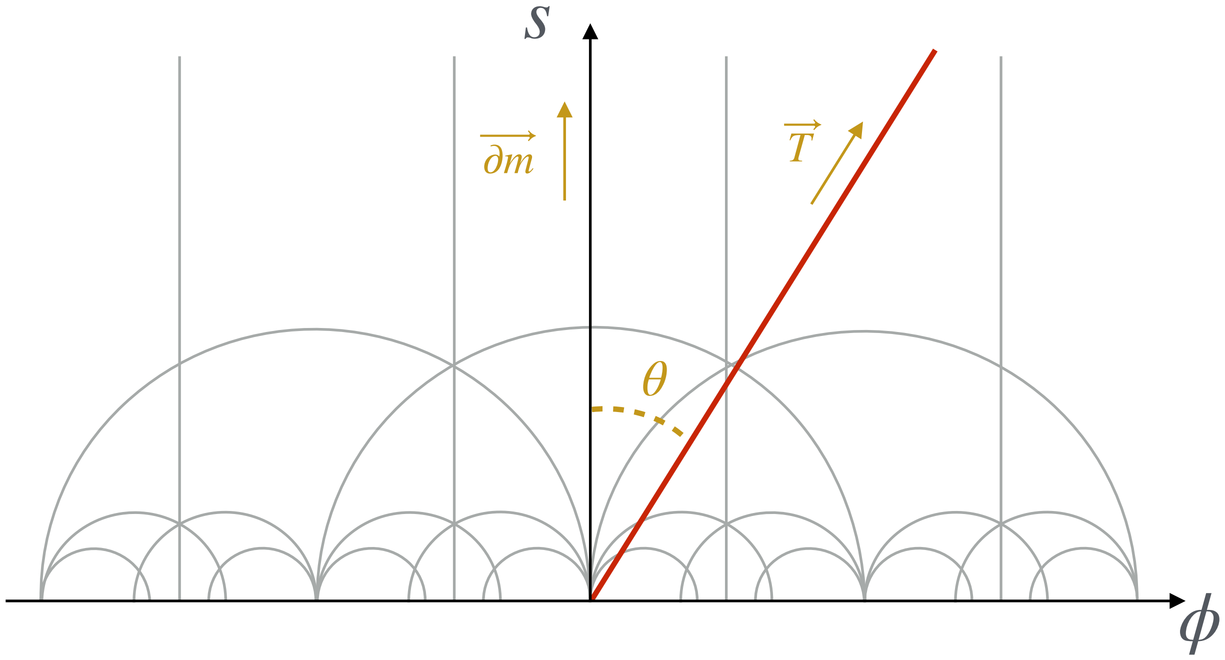

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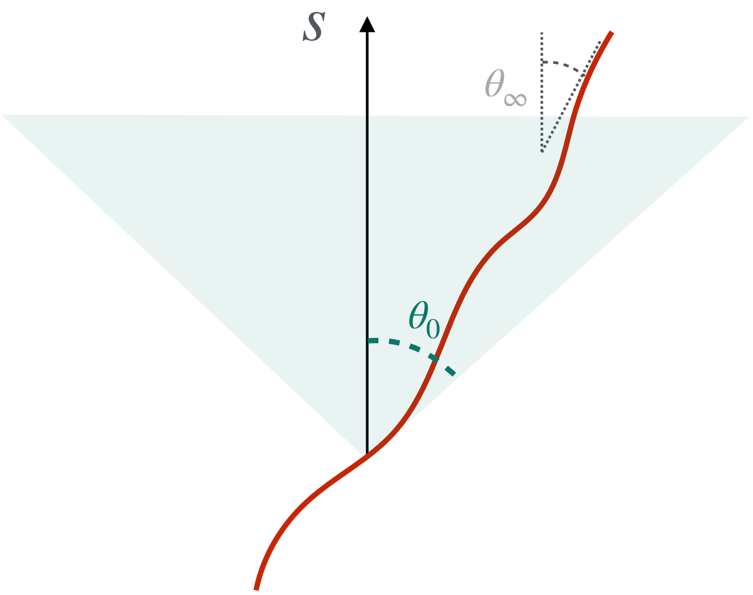
$$\frac{\Omega}{H} = \frac{|\sin\theta|}{n}\sqrt{2\epsilon}$$

$$\frac{\Omega}{H} < \frac{\sqrt{\lambda_0^2 - \lambda_g^2}}{\lambda_g}\sqrt{R\ \epsilon}$$

Moving away from the boundary of moduli space

Freigang, Lüst, Nian, MS 2023

- **Asymptotic expansion of θ**



$$\theta(s) = \theta_\infty + \sum_{n>0} \frac{c_n}{s^n}$$

consider just leading non-constant term

$$\theta(s) \simeq \theta_\infty + \frac{c_k}{s^k}$$

$$\theta(s) \leq \theta_0$$

$$\frac{c_k}{s^k} \leq \theta_0 - \theta_\infty \leq 2\theta_0$$

$$\left|\dot{\theta}(s)\right| \approx \frac{k}{n}\frac{c_k}{s^k} \cos\theta(s)\ \dot{\Phi} \leq \frac{2k}{n}\theta_0 \cos\theta(s)\ \dot{\Phi}$$

$$\boxed{\left|\frac{\dot{\theta}(s)}{H}\right| \leq 2\sqrt{2}\ \frac{k}{n}\ \theta_0\ \sqrt{\epsilon}}$$

$$\boxed{\frac{\Omega}{H} \simeq \sqrt{\epsilon}}$$

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Lüst, Masias, Pieroni, Scalisi - work in progress

$$\mathscr{L} = -\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - \frac{1}{2}\sum_i \left[(\partial\chi_i)^2 - m_n^2 e^{-2\lambda\varphi}\chi_n^2\right]$$

mass of the SDC tower

$$m \sim e^{-\lambda\varphi}$$

use conformal time $t \to \tau$

rescale modes $\chi_n \to \xi_n / a$

Equation of motion for the Fourier modes

$$\xi_n''(\tau, \overrightarrow{k}) + \left[k^2 - \frac{2-\delta_n}{\tau^2}\right]\xi_n(\tau, \overrightarrow{k}) = 0$$

with $\delta_n = \dfrac{m_n^2}{H^2}\exp(-2\lambda\varphi)$

Two-point correlation function

$$\langle : \chi_n \ \chi_n : \rangle = \frac{1}{a}\frac{3}{8\pi^2}\frac{H^2}{m_n^2 \exp(-2\lambda\varphi)\tau^2}$$

$$\sum_n^{N_H} \frac{m_n^2}{2} e^{-2\lambda\varphi}\langle : \chi_n \ \chi_n : \rangle = \frac{3}{16\pi^2}H^4 N_H$$

Multi-field cosmic acceleration

Achucarro, Palma 2018
Freigang, Lüst, Nian, MS 2023

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$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\Phi}^2}{2H^2}$$ *acceleration parameter*

$$\eta \equiv \frac{\dot{\epsilon}}{H\epsilon} = 2\epsilon + 2\frac{\ddot{\Phi}}{H\dot{\Phi}}$$ *eta parameter*

$$\frac{|\nabla V|^2}{V^2} = 2\epsilon\left(\left(1 + \frac{\eta}{2(3-\epsilon)}\right)^2 + \frac{\Omega^2}{H^2(3-\epsilon)^2}\right)$$

$\epsilon < 1$

$$\frac{|\nabla V|^2}{V^2} \simeq 2\epsilon\left(\left(1 + \frac{\eta}{6}\right)^2 + \frac{\Omega^2}{9H^2}\right)$$

$\eta, \epsilon \ll 1$ slow roll

$$\frac{|\nabla V|^2}{V^2} \simeq 2\epsilon\left(1 + \frac{\Omega^2}{9H^2}\right)$$

Decay rate in the **axion-saxion model**

*Valenzuela & **MS** 2018*

$$\mathscr{L} = \frac{n^2}{s^2}\left(\underbrace{\dot{s}^2}_{\text{saxion}} + \underbrace{\dot{\phi}^2}_{\text{axion}}\right)$$

$$\boxed{(s, \phi) = (s_0 + \delta s, \frac{1}{a}\delta s)}$$

trajectory

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saxion

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(axion-saxion backreaction in String Theory)

Blumenhagen, Font, Fuchs, Herschmann, Plauschinn 2015
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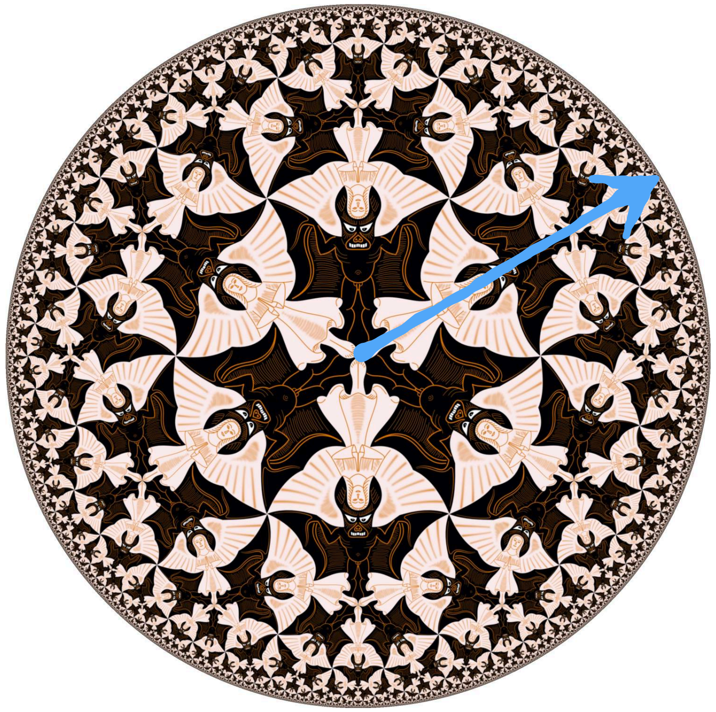

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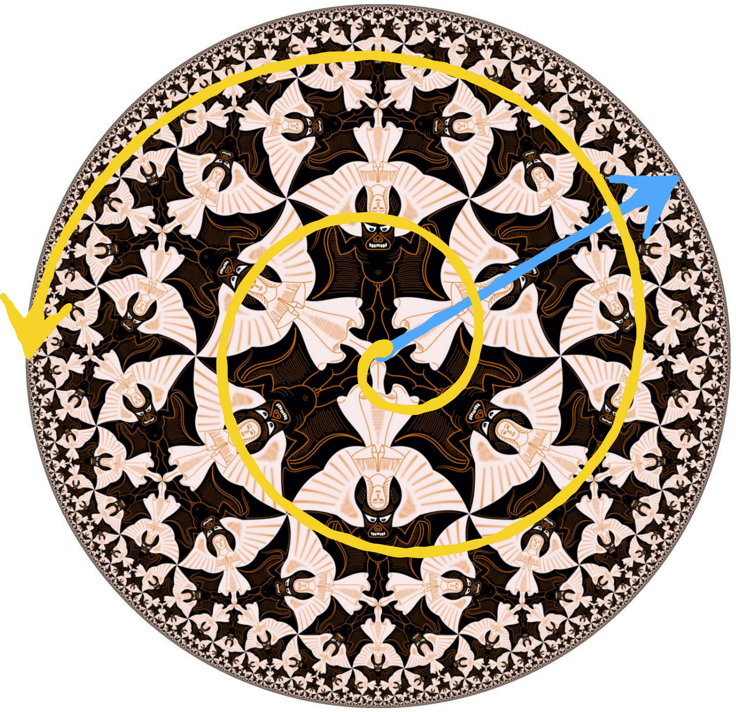
Valenzuela 2016
Blumenhagen 2018



Decay rate in the **axion-saxion model**

*Valenzuela & **MS** 2018*

$$\mathcal{L} = \frac{n^2}{s^2}\left(\dot{s}^2 + \dot{\phi}^2\right)$$

saxion

axion

$$\boxed{(s, \phi) = (s_0 + \delta s, \frac{1}{a}\delta s)}$$

trajectory

$$\lambda \to \lambda_{eff} = \lambda\frac{a}{\sqrt{1 + a^2}}$$

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$a \to \infty$

$\lambda_{eff} \sim \lambda$

trajectory mainly saxionic

$a \to 0$

$\lambda_{eff} \ll \lambda$

trajectory mainly axionic