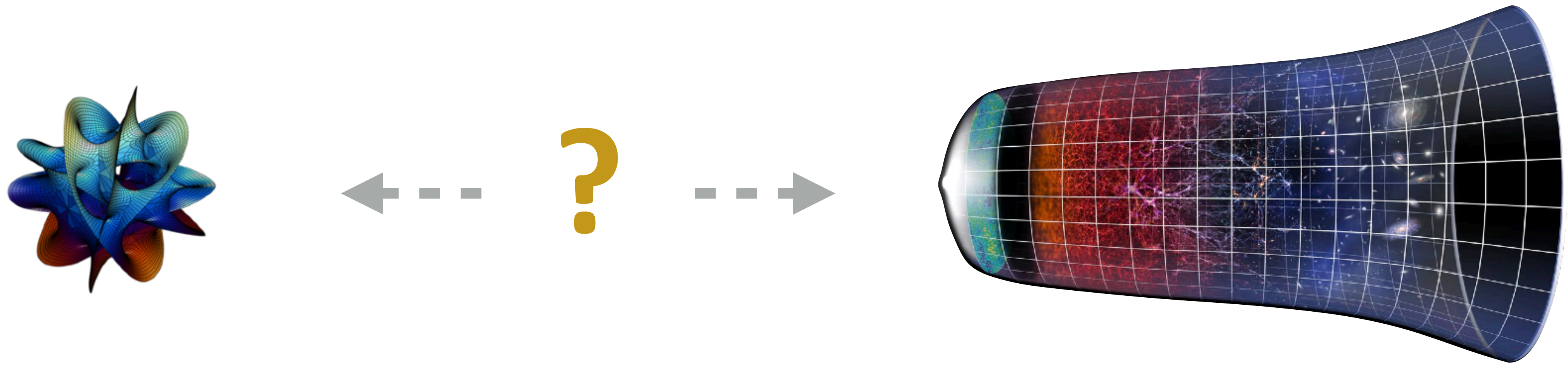
Species Cosmology

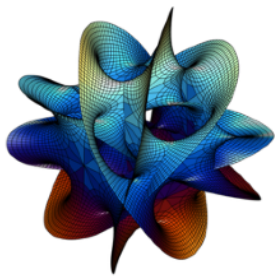
based on ***2401.09533*** *and on* ***work in progress*** *with D.Lüst, J.Masias, M.Pieroni*

Marco Scalisi

March 19th, 2024
Ringberg Castle, Tegernsee

MAX-PLANCK-INSTITUT
FÜR PHYSIK





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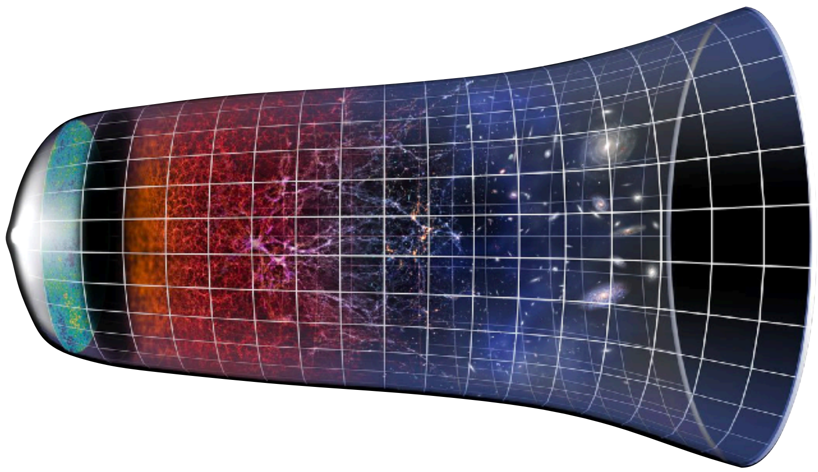
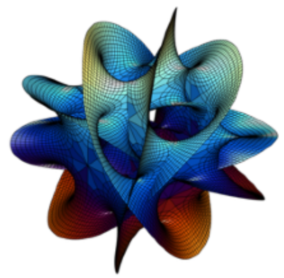


M_{P}

$H \lesssim 10^{-5}\, M_{\mathrm{P}}$



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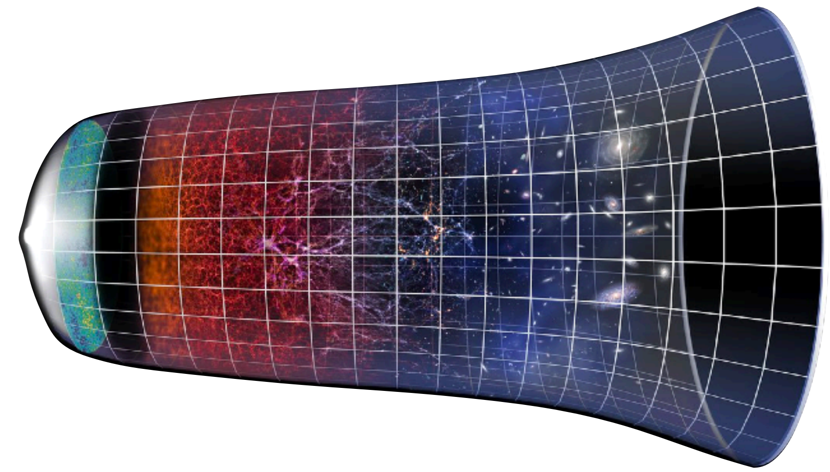
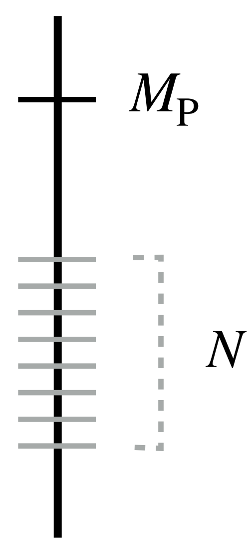
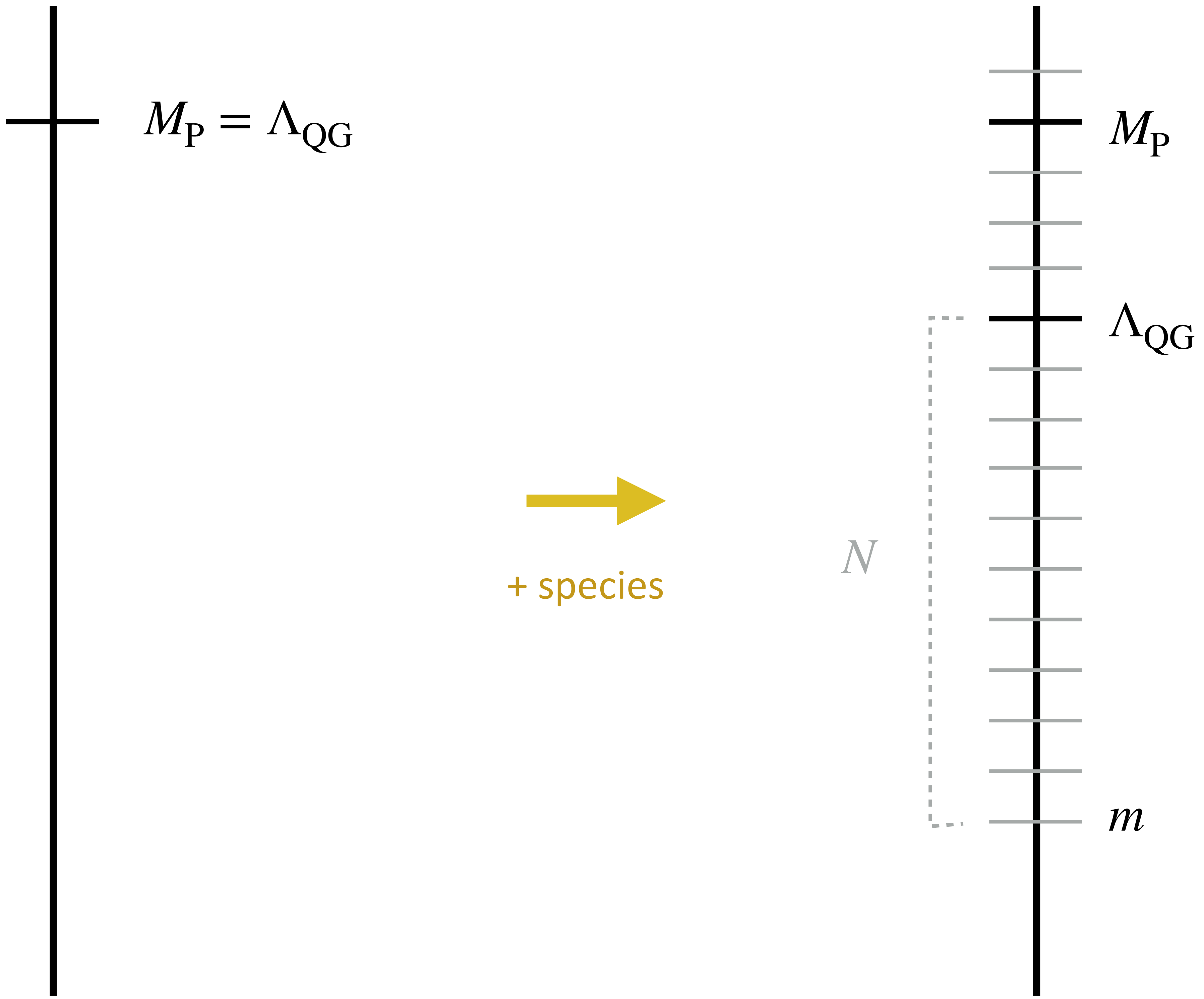




Species

$$\Lambda_{QG} < M_P$$


$M_P = \Lambda_{QG}$
+ species
M_P
Λ_{QG}
N
m

OUTLINE

The Species Scale

Species $\rightarrow$ Cosmology

Species $\leftarrow$ Cosmology

The Species Scale

Species scale

Dvali, 2007

Dvali, Redi 2007

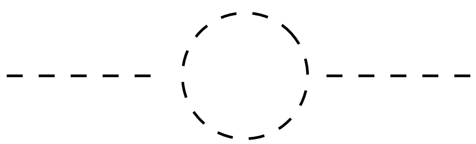
Species scale

Dvali, 2007

Dvali, Redi 2007

Perturbative argument

N light species weakly coupled to gravity



contribution to
graviton propogator

$$\pi^{-1}(p^2) = p^2 \left[1 - \frac{N\, p^2}{120\pi\, M_{\rm P}^2} \log\left(-\frac{p^2}{\mu^2} \right) \right]$$

tree level

1-loop

Species scale

Dvali, 2007

Dvali, Redi 2007

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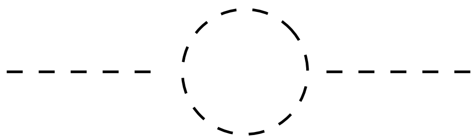

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perturbation theory breaks down when
tree level = 1-loop

$$p \sim \frac{M_{\mathrm{P}}}{\sqrt{N}} \equiv \Lambda_{\mathrm{s}}$$

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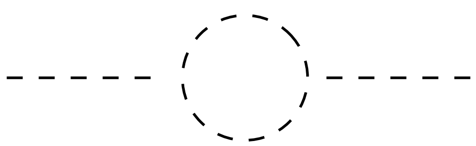

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Non-perturbative argument

Black hole with N species

What is its **minimal radius**?

Species scale

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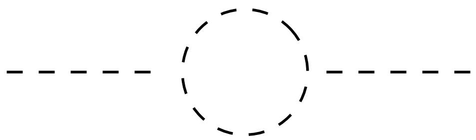

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$$R_{\rm BH} \simeq \frac{1}{M_{\rm P}}$$

corresponds to

$$S_{\rm BH} \simeq R_{\rm BH}^{d-2} M_{\rm P}^{d-2} = 1$$

⚠

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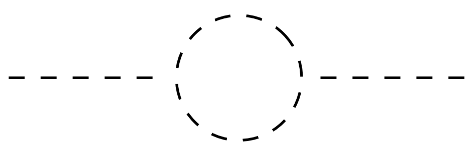

contribution to **graviton propogator**

$$\pi^{-1}(p^2) = p^2 \left[1 - \frac{N\, p^2}{120\pi\, M_P^2} \log\left(-\frac{p^2}{\mu^2} \right) \right]$$

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$$p \sim \frac{M_P}{\sqrt{N}} \equiv \Lambda_s$$

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Black hole with N species

What is its **minimal radius**?

$$R_{BH} \simeq \frac{1}{M_P}$$

corresponds to

$$S_{BH} \simeq R_{BH}^{d-2} M_P^{d-2} = 1$$

↓

Conundrum resolved if

$$R_{min} \simeq N^{\frac{1}{d-2}} M_P^{-1} = \Lambda_s^{-1}$$

Species scale

Dvali, 2007

Dvali, Redi 2007

Λ_s =

- scale at which **gravity** becomes **strongly coupled**
- scale of the **minimal size** of BH
- scale of higher curvature corrections

= Λ_{QG}

$$\Lambda_{QG} = \frac{M_P}{N^{\frac{1}{d-2}}}$$

(renormalization of the Planck mass)

Species scale

Dvali, 2007
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= $\Lambda_{\rm QG}$

$$\Lambda_{\rm QG} = \frac{M_{\rm P}}{N^{\frac{1}{d-2}}}$$

(renormalization of the Planck mass)

At this scale
EFT has **holographic properties**

$$S \sim \Lambda_{\rm QG}^{-(d-2)}$$

Cribiori, Lüst, Montella 2023
Herraez, Lüst, Masias, MS - work in progress

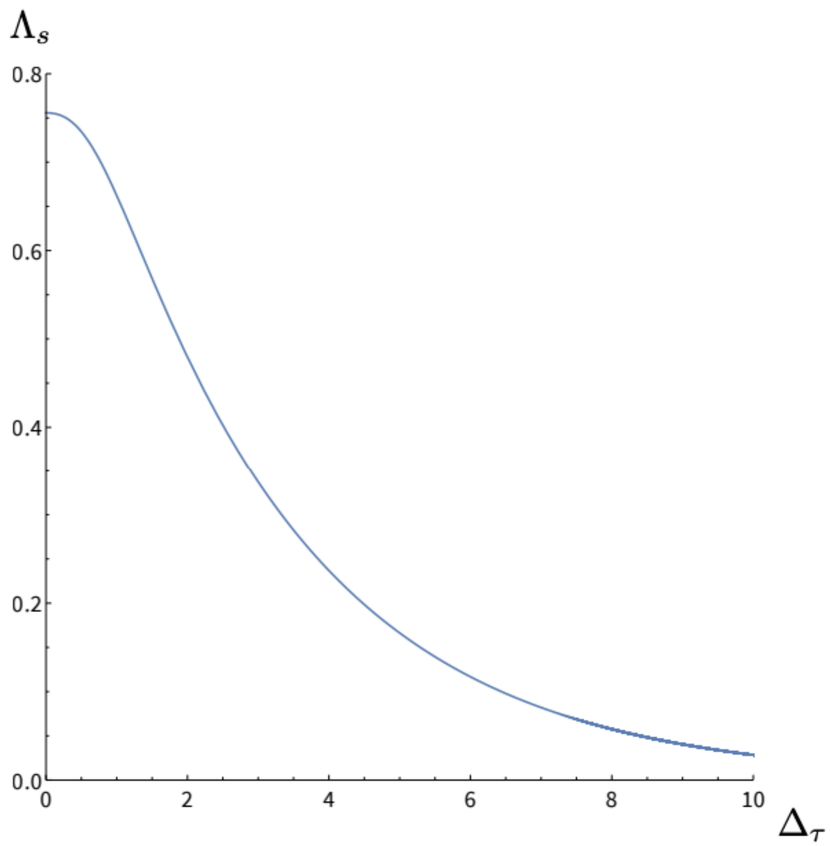
in string theory

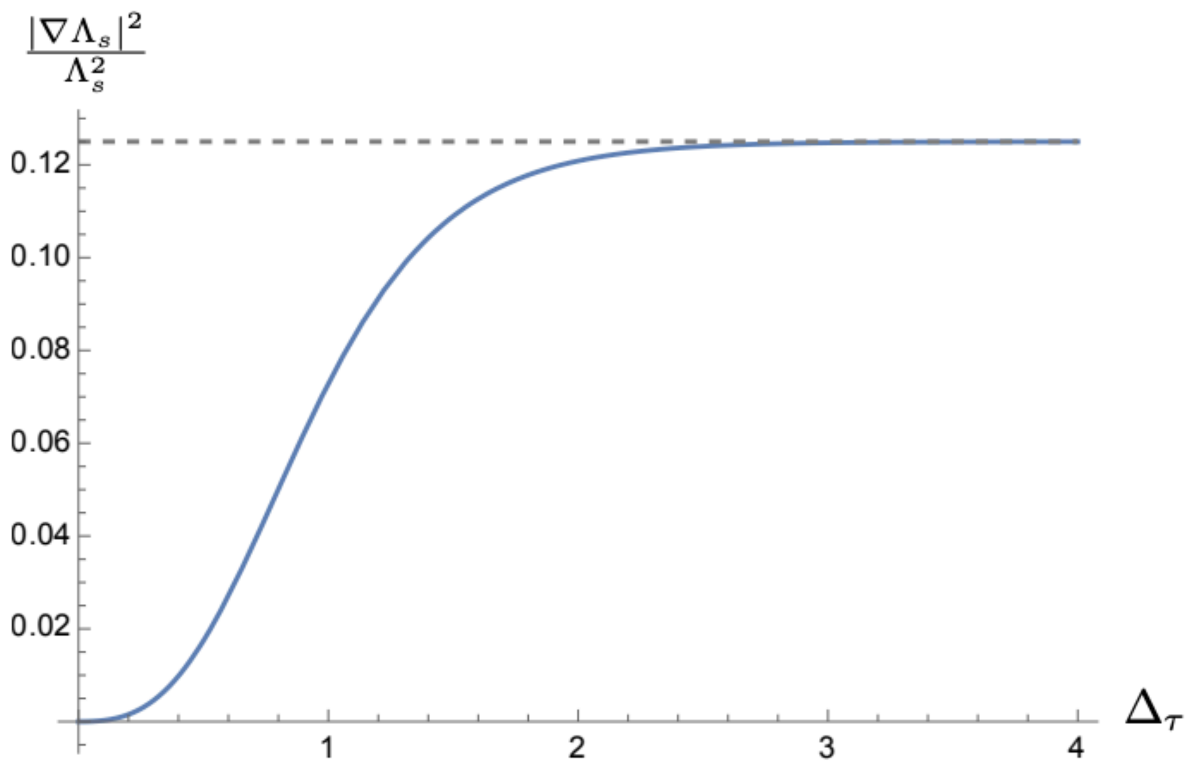
Kaluza-Klein modes

String oscillator modes

Lee, Lerche, Weigand 2019

Species scale





Species scale for ten-dimensional **Type IIB**

from van de Heisteeg, Vafa, Wiesner, Wu 2023

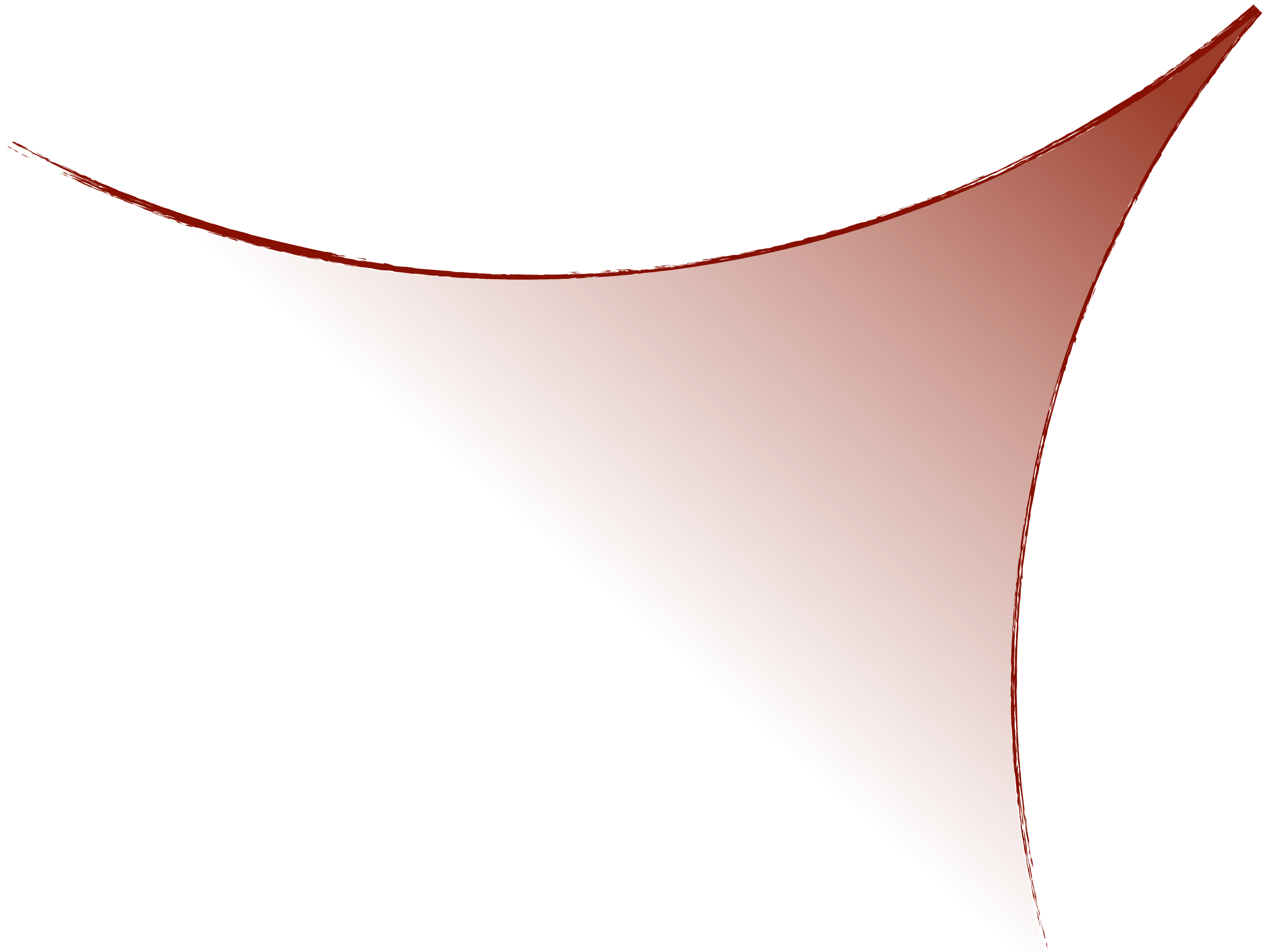
Species scale

$$\frac{1}{\sqrt{(d-1)(d-2)}} \leq \left| \frac{\Lambda'_{\mathrm{QG}}}{\Lambda_{\mathrm{QG}}} \right| \leq \frac{1}{\sqrt{d-2}}$$

van de Heisteeg, Vafa, Wiesner, Wu 2023
Calderón-Infante, Castellano, Herráez, Ibánez 2023

van de Heisteeg, Vafa, Wiesner, 2023
van de Heisteeg, Vafa, Wiesner, Wu 2023
*Lüst, Masias, Muntz, **MS** 2023*

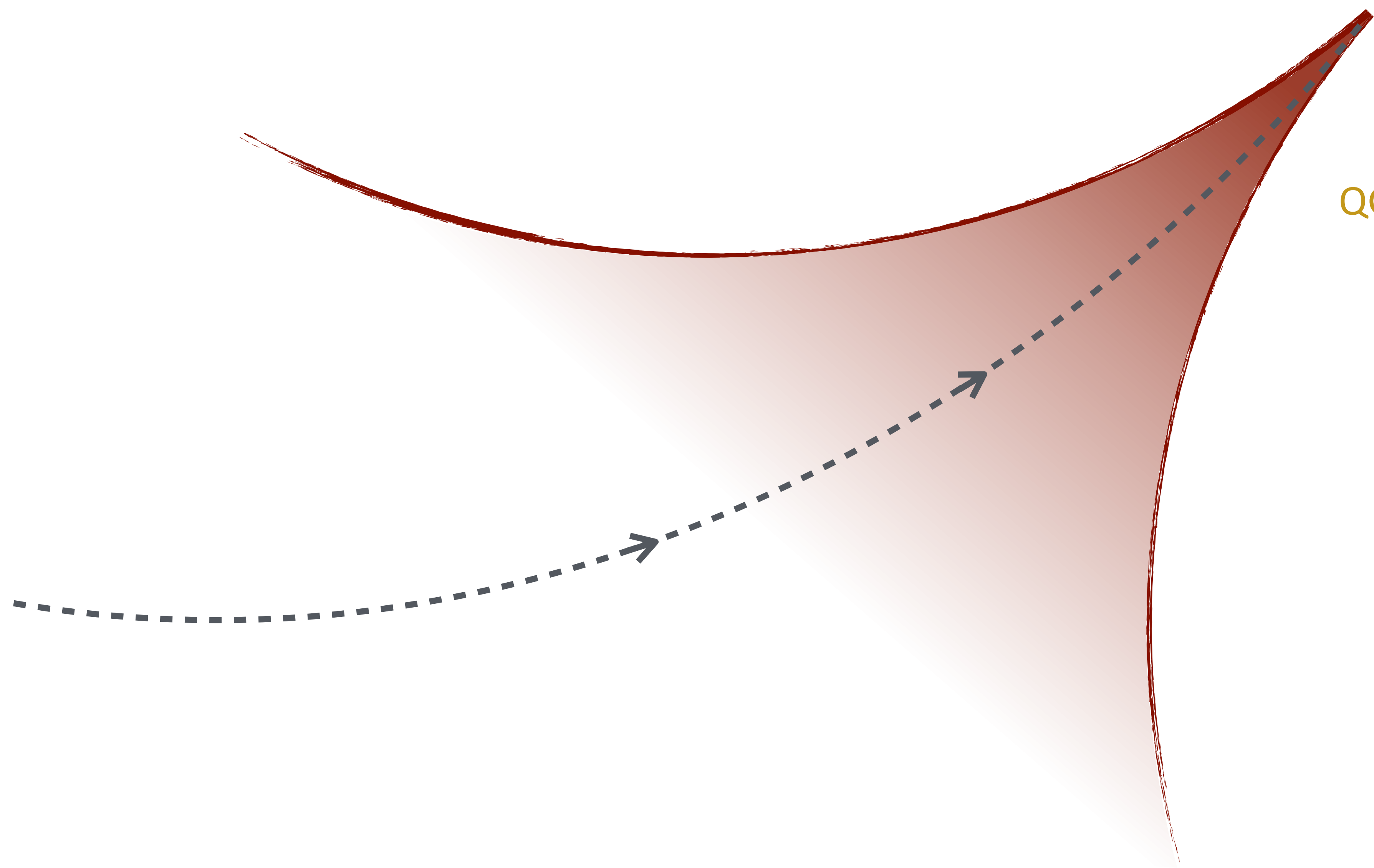
Species and the **Swampland**



Species and the **Swampland**

$m \to 0$

mass of infinite tower of **species**

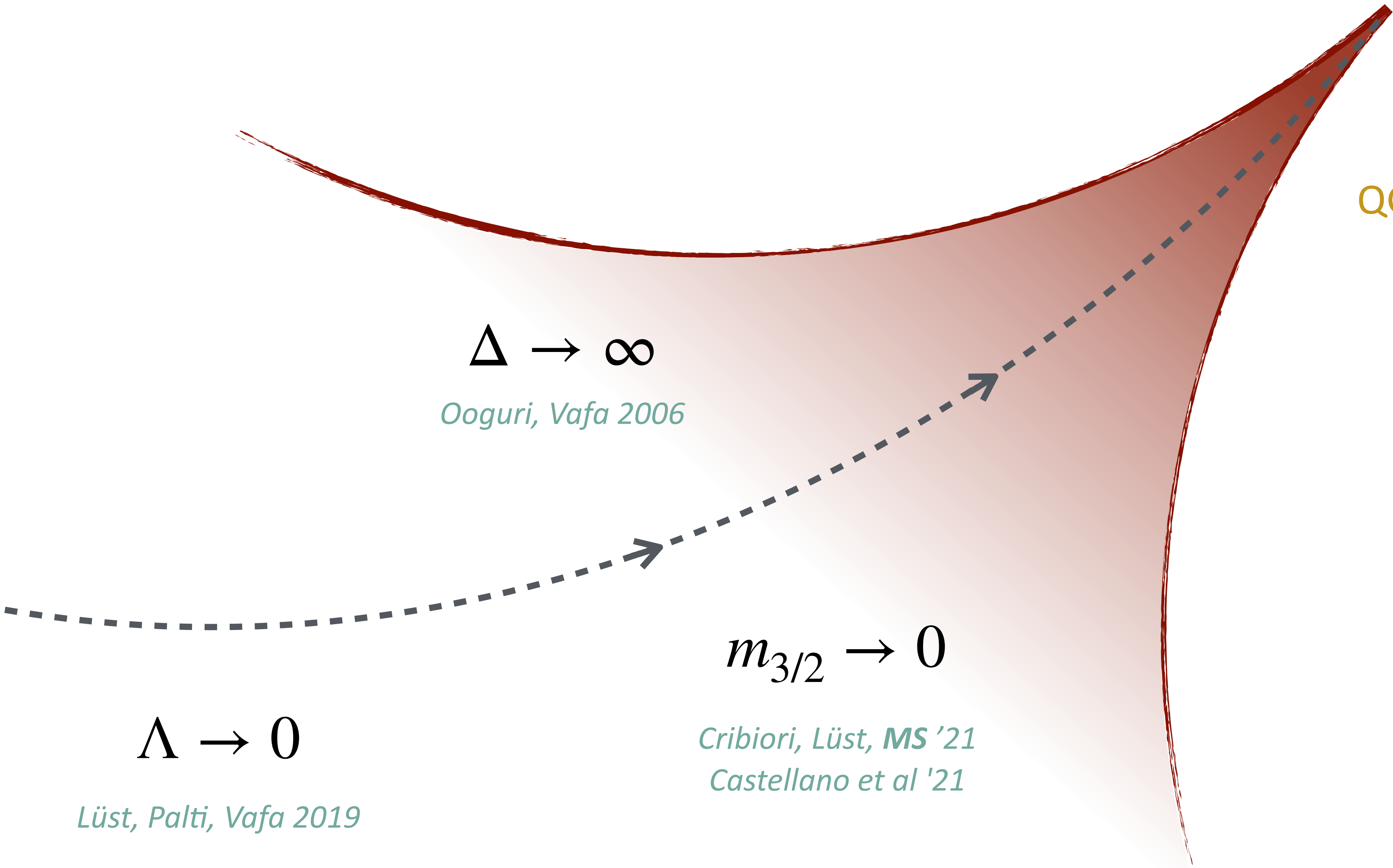


$\Lambda_{\text{QG}} \to 0$

QG cut-off = **species scale**

Dvali 2007

Species and the **Swampland**



Swampland Distance Conjecture

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

$$m = m_0\, e^{-\gamma\Delta} \qquad\qquad \Delta \to \infty$$

Ooguri, Vafa 2007

Swampland Distance Conjecture

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

$$m = m_0 \, e^{-\gamma \Delta} \qquad \Delta \to \infty$$

exponential drop-off of the QG cut-off

$$\Lambda_{\text{QG}} = \Lambda_0 \, e^{-\lambda \Delta}$$

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

Species and the **Swampland**

Ooguri, Vafa 2007

universal bound on scalar **field variation**

$$\Delta \leq \frac{1}{\lambda} \log \frac{M_{\mathrm{P}}}{\Lambda_{\mathrm{QG}}}$$

Species and the **Swampland**

Ooguri, Vafa 2007

universal bound on scalar **field variation**

$$\Delta \leq \frac{1}{\lambda} \log \frac{M_{\rm P}}{\Lambda_{\rm QG}}$$

Certain scalar **variations** allowed at the cost of **decreasing** the quantum gravity **cut-off**

$\Lambda_{\rm QG} \to M_{\rm P}$

implies

$\Delta \to 0$

Infinite scalar field **variations** **prohibited** since it corresponds to $\Lambda_{\rm QG} \to 0$ (**breakdown of EFT**)

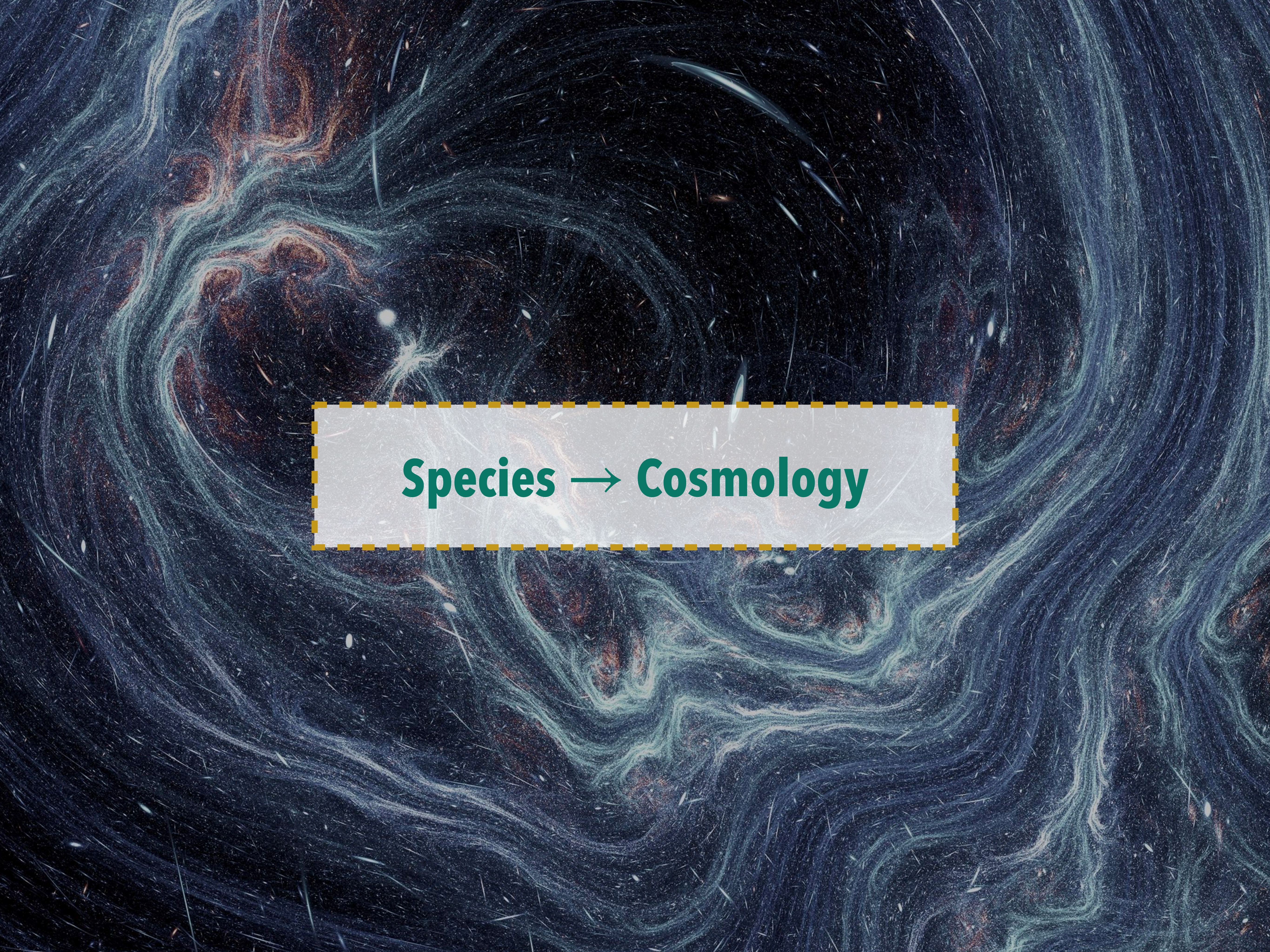
Main message

- **Towers of states** lead to a **renormalization** of the **quantum gravity cut-off**

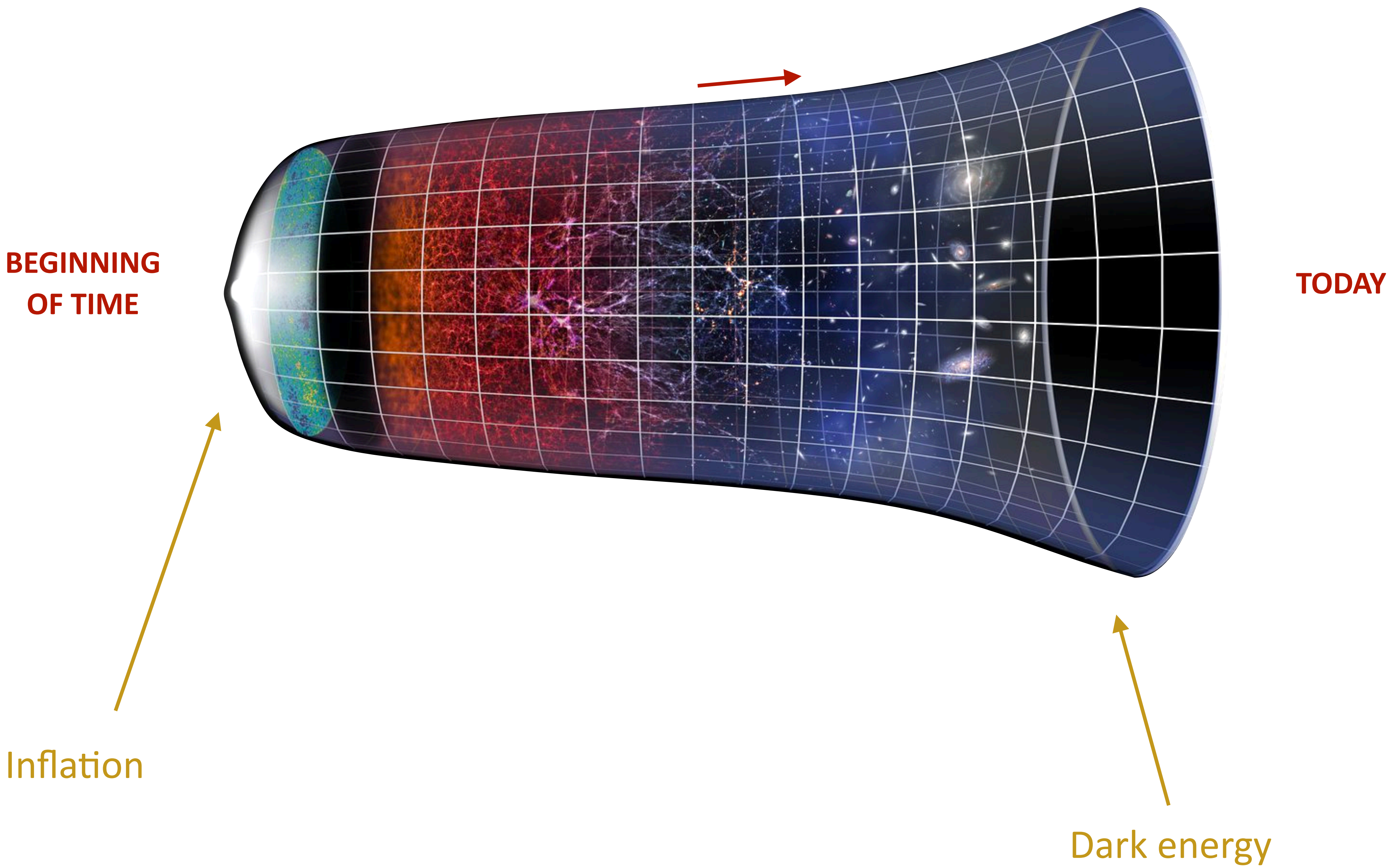
$$\Lambda_{\mathrm{QG}} = \frac{M_{\mathrm{P}}}{N^{\frac{1}{d-2}}} < M_{\mathrm{P}}$$

- **Distance conjecture** implies **exponential drop-off** in field space of Λ_{QG}

$$\Lambda_{\mathrm{QG}} \sim e^{-\lambda \Delta}$$

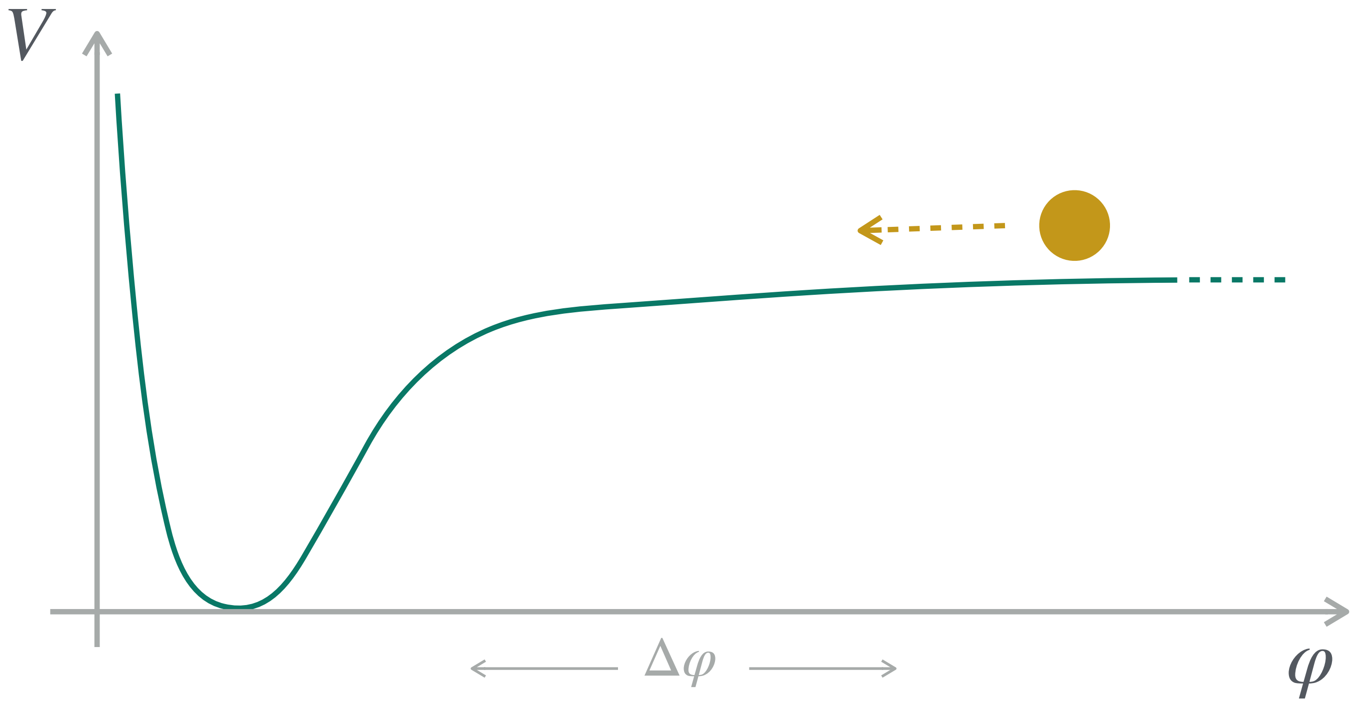

Species → Cosmology

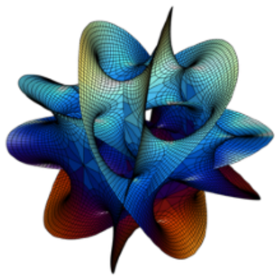
Focus on **cosmic acceleration**

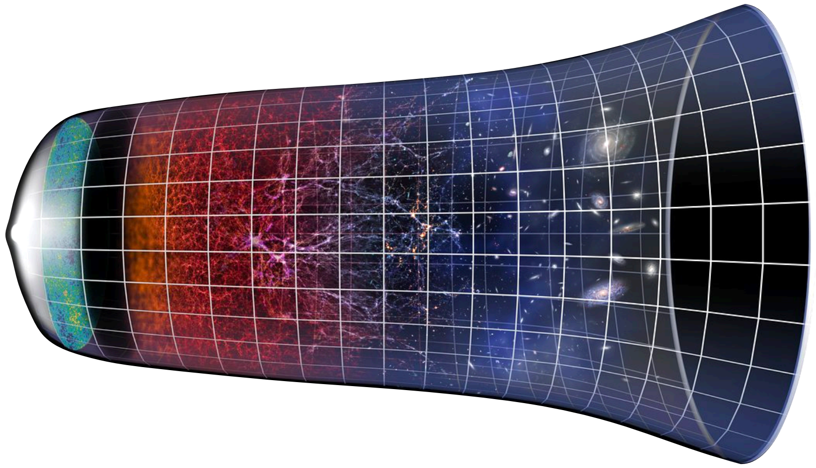


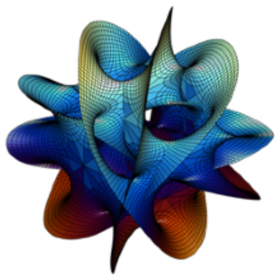
Focus on **cosmic acceleration**

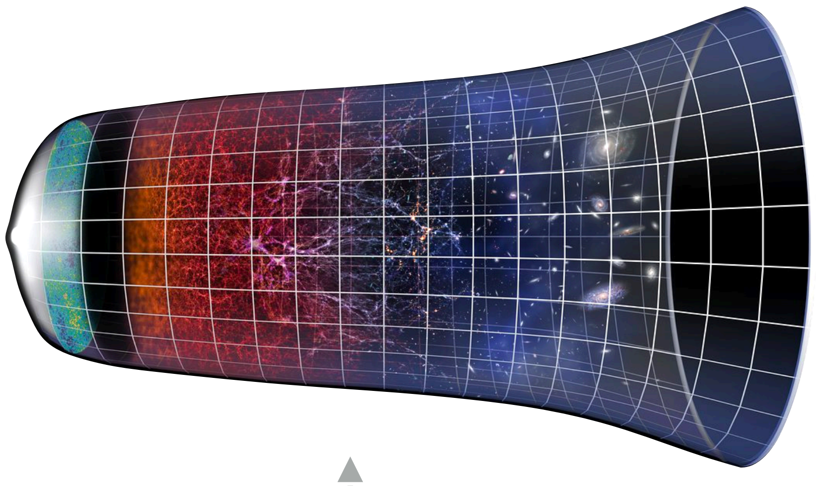
time-dependent cosmic acceleration











Λ_{QG}

- Universal **upper bound** on $\Delta\varphi$
- Cosmological **species production**

Universal upper bound on scalar field range

MS, Valenzuela 2018

$$H < \Lambda_{QG} \leq M_{\rm P}\, e^{-\lambda \Delta\varphi}$$

consistency of EFT *implication of the SDC*

Universal upper bound on scalar field range

MS, *Valenzuela 2018*

see also

van de Heisteeg, Vafa, Wiesner, Wu 2023

$$H < \Lambda_{QG} \leq M_{\rm P}\, e^{-\lambda \Delta\varphi}$$

consistency of EFT   *implication of the SDC*

upper bound on field displacement

$$\Delta\varphi < \frac{1}{\lambda} \log \frac{M_{\rm P}}{H}$$

Universal upper bound on scalar field range

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dark energy

$$\Delta\varphi \lesssim 140\; M_{\rm P}$$

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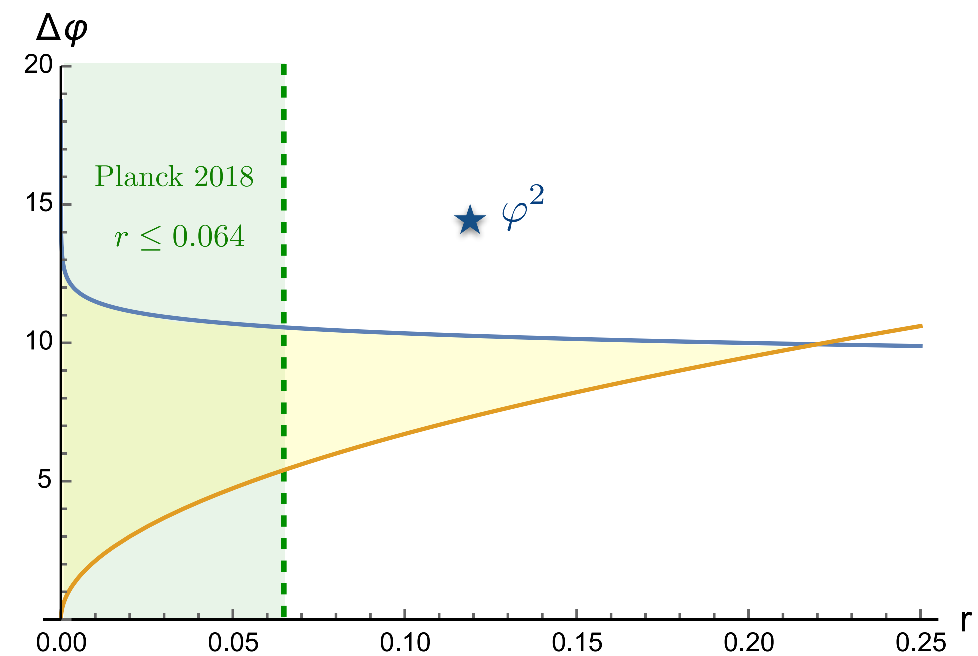
$$\Delta\varphi \lesssim 140\, M_{\rm P}$$

inflation

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



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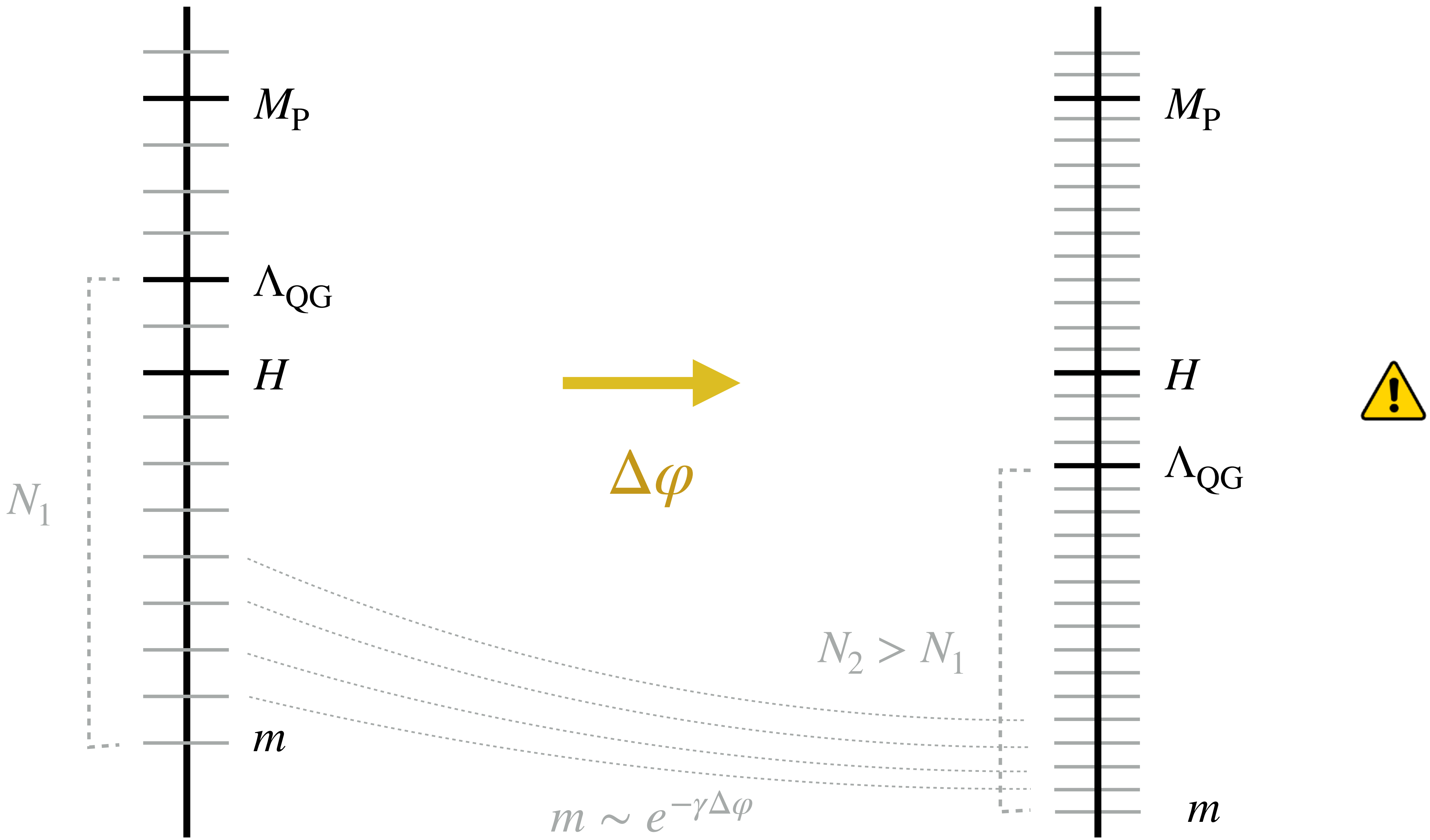
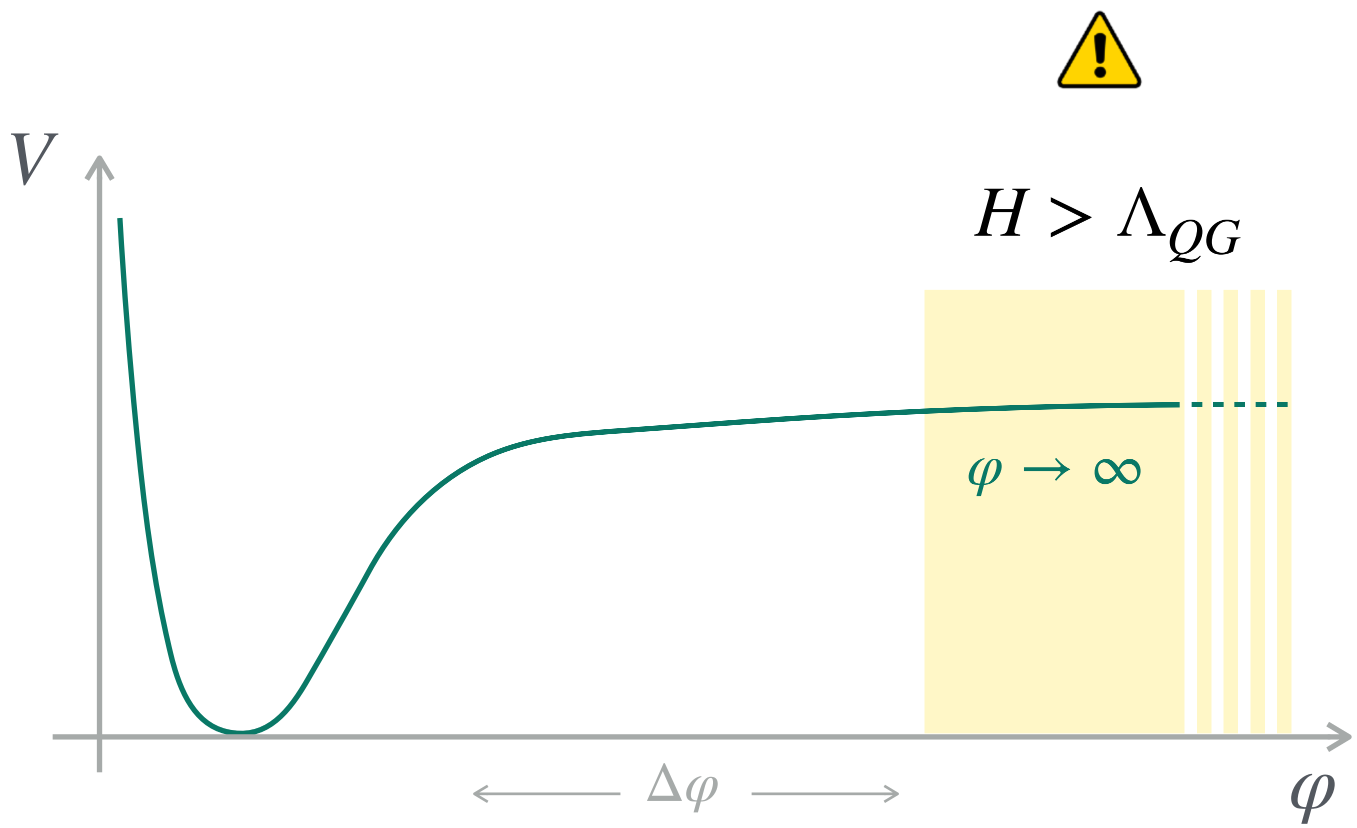


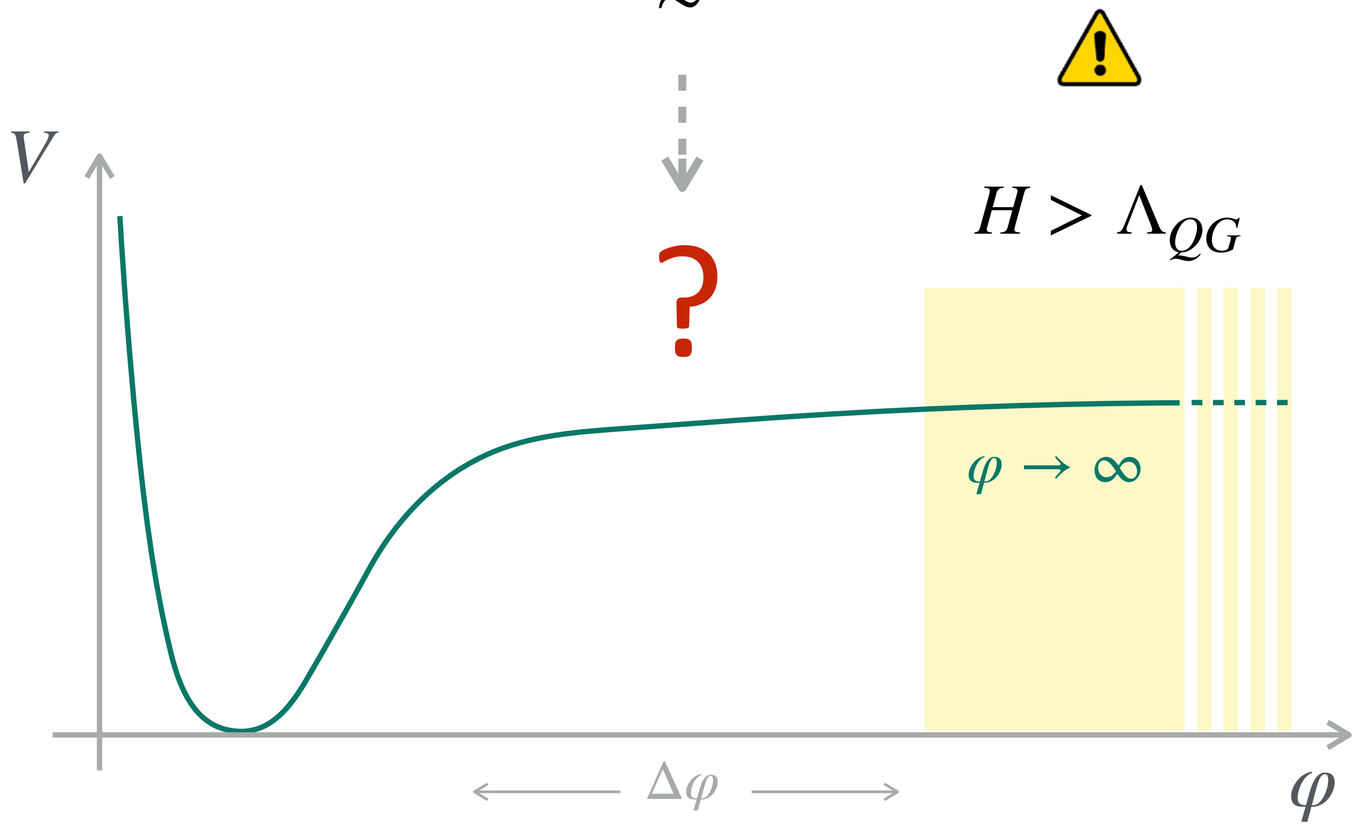
Inflationary **particle production** and the **Swampland**

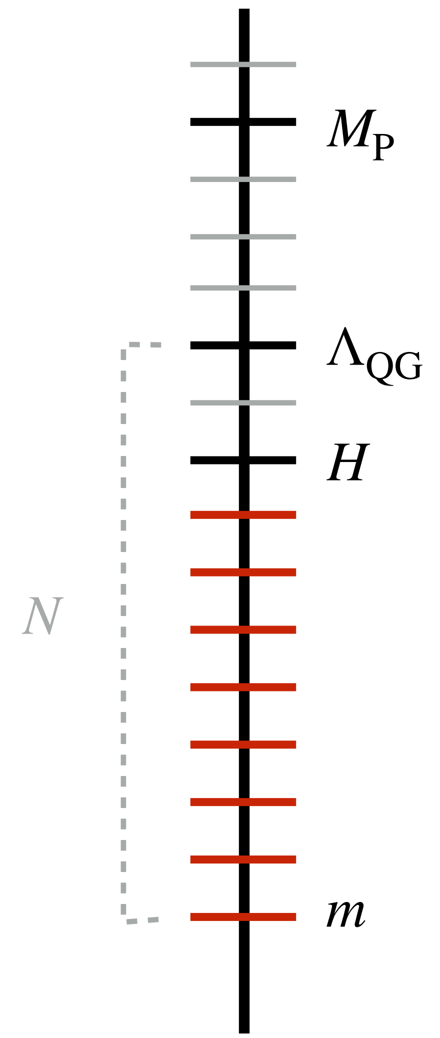
Lüst, Masias, Pieroni, MS - work in progress



Lüst, Masias, Pieroni, MS - work in progress

$m \lesssim H$





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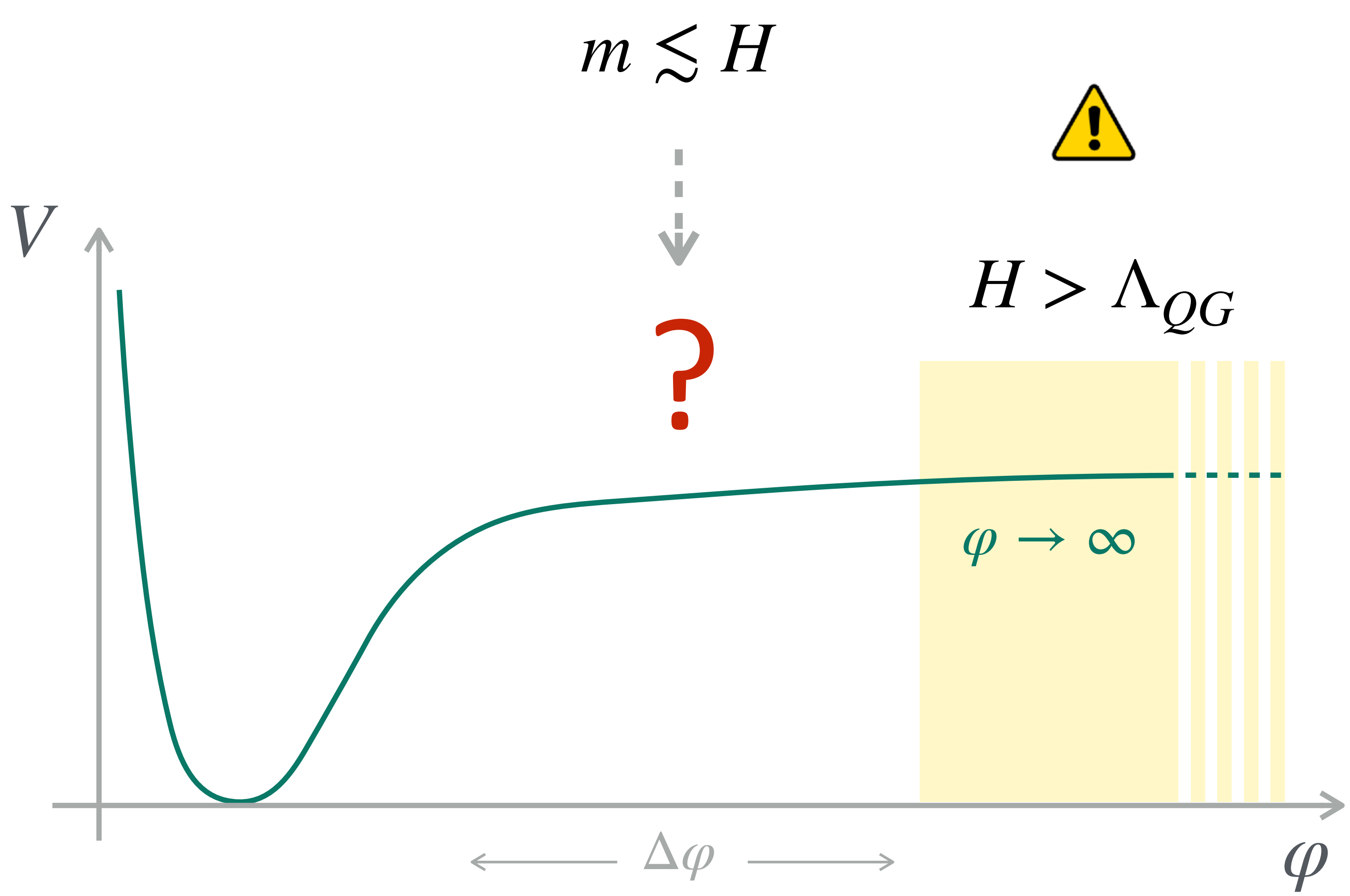

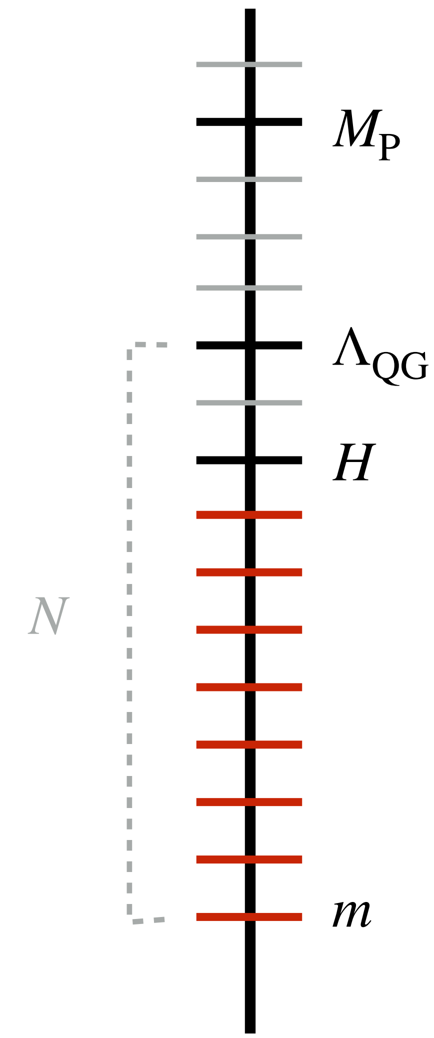

Species production

Inflationary **particle production** and the **Swampland**

Lüst, Masias, Pieroni, MS - work in progress

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

Inflationary **particle production** and the **Swampland**

Lüst, Masias, Pieroni, MS - work in progress

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

- **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"*

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

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

mass of the SDC tower

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

Inflationary **particle production** and the **Swampland**

Lüst, Masias, Pieroni, MS - work in progress

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mass of the SDC tower

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

with

$$\delta_n = \frac{m_n^2}{H^2}e^{-2\gamma\varphi}$$

$$\xi_n \equiv a(\tau)\chi_n$$

$$\xi_n(\tau, \vec{k}) = \frac{\sqrt{-\pi}}{2}\exp\left[\frac{i\pi}{4}\sqrt{9-4\delta_n} + \frac{i\pi}{4}\right]\sqrt{-\tau}\, H^{(1)}_{\frac{1}{2}\sqrt{9-4\delta_n}}(-k\tau)$$

$H^{(1)}$= *Bessel function of the 3rd kind (or Hankel function of the 1st kind)*

Inflationary **particle production** and the **Swampland**

Lüst, Masias, Pieroni, MS - work in progress

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

mass of the SDC tower

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main result

$$\text{corrections} \propto \left(\frac{H}{\Lambda_{\rm QG}}\right)^{2+p}$$

$p = 1$

- **Scalar power spectrum**

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

- **Non Gaussianities**

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

- **Tensor-to-scalar ratio**

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

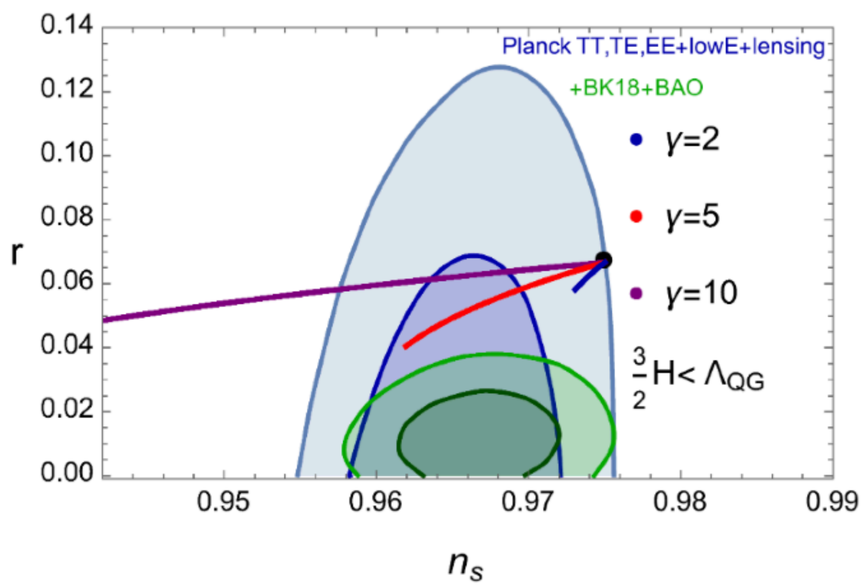
- **Scalar spectral tilt**

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

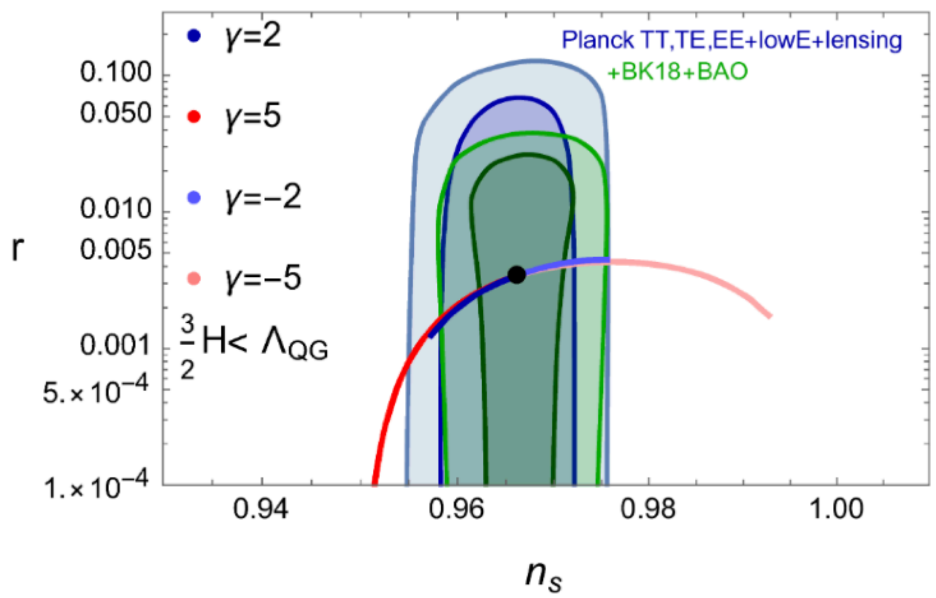
Inflationary **particle production** and the **Swampland**

Lüst, Masias, Pieroni, MS - work in progress

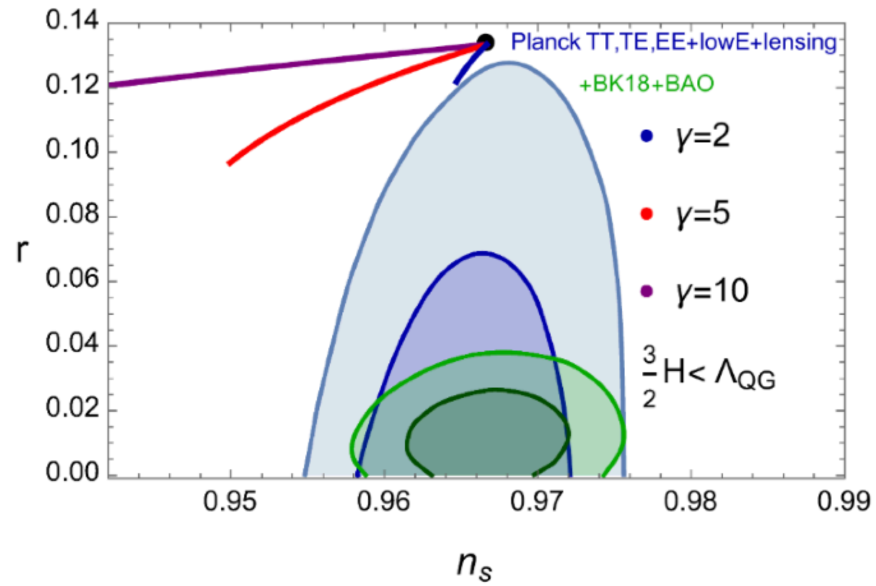
$$V \sim \varphi$$



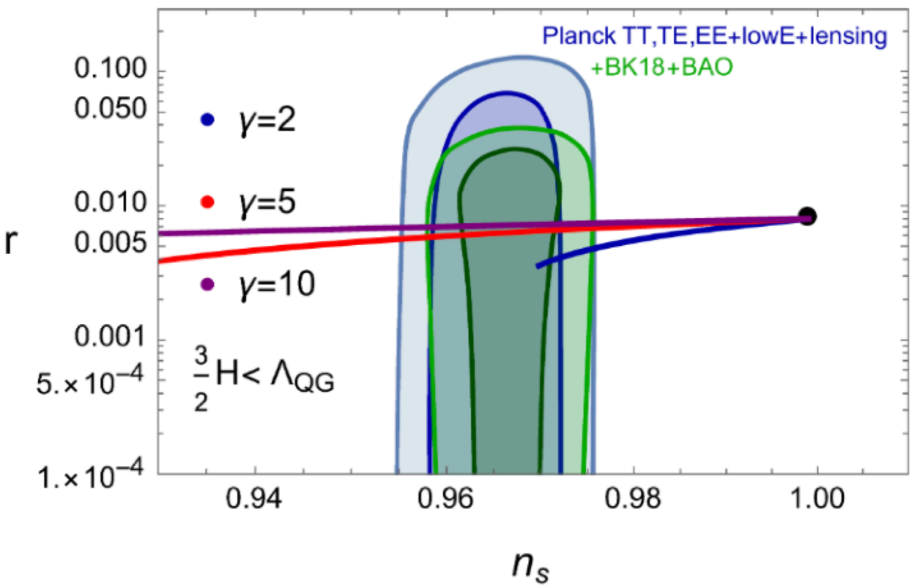
$$V \sim \left(1 - e^{\sqrt{2/3}\,\varphi}\right)^2$$



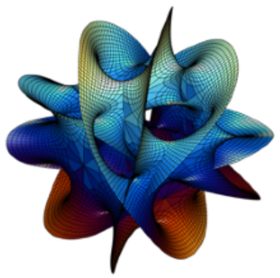
$$V \sim \varphi^2$$

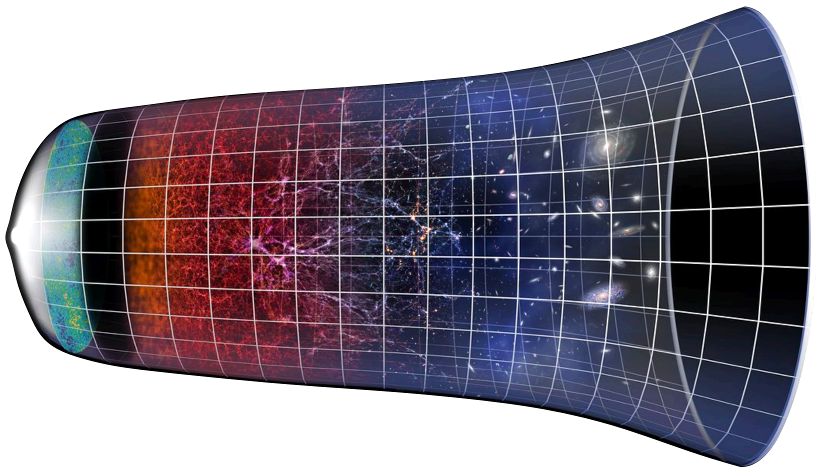


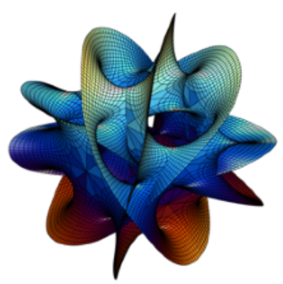
$$V \sim e^{\varphi}$$

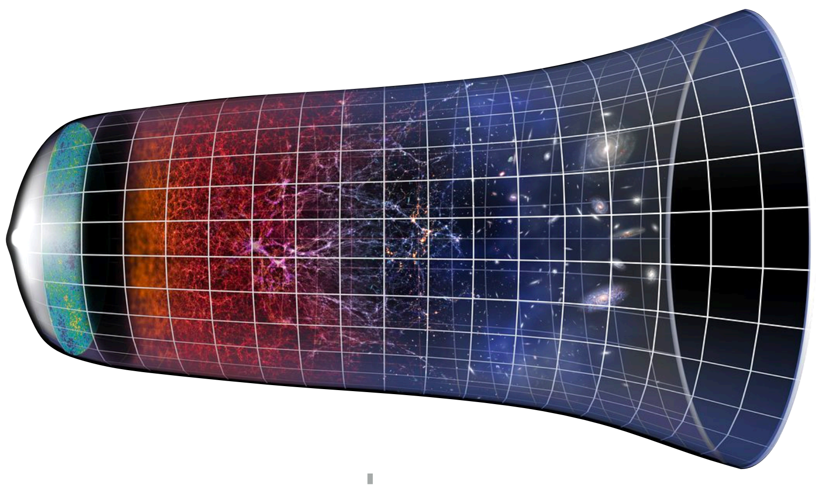


Species ← Cosmology







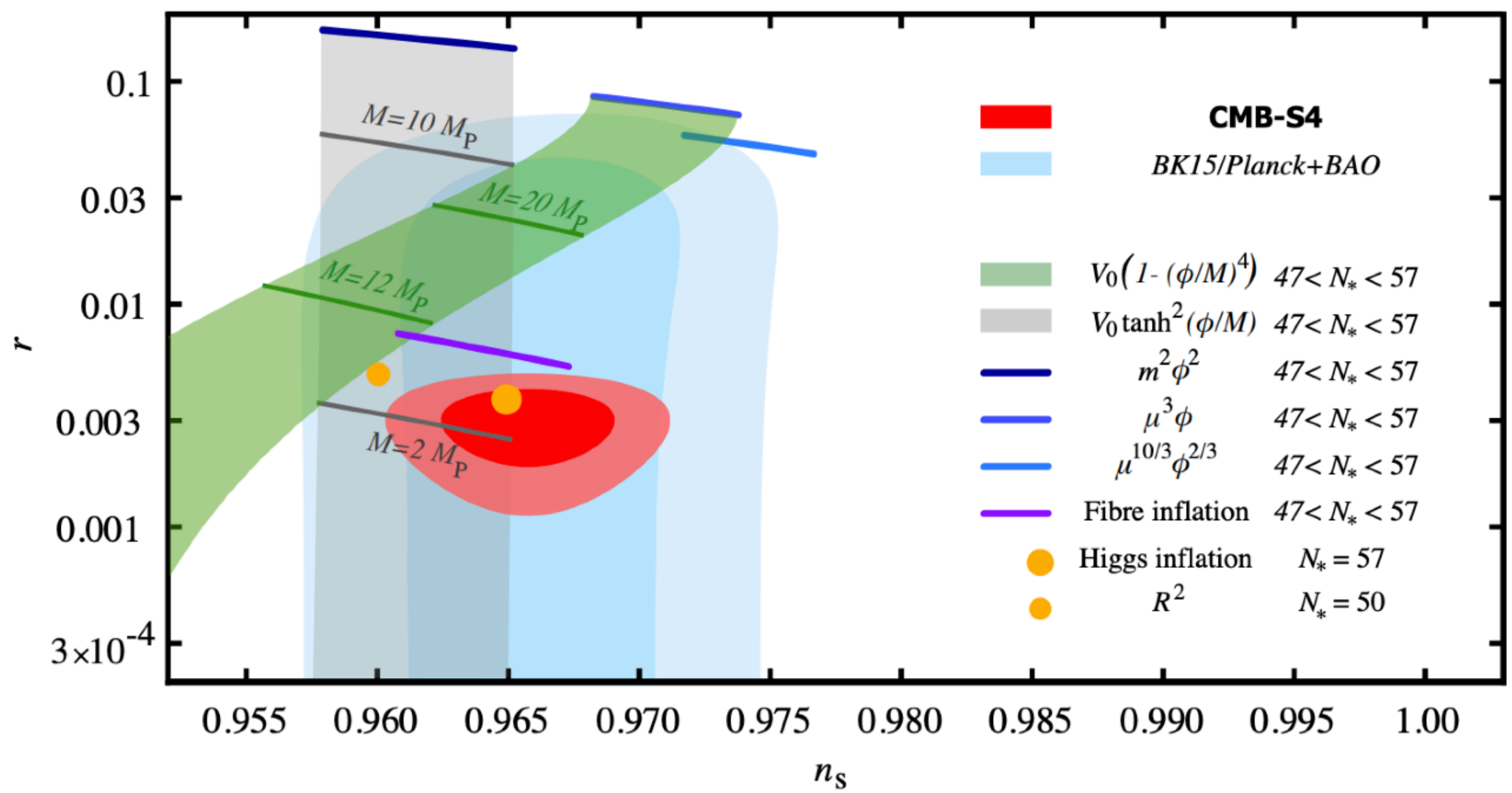


$$\left|\frac{\Lambda_s'}{\Lambda_s}\right| \leq \frac{c}{\sqrt{r}} \log \frac{10^8}{r}$$

r

Species scale and **primordial gravitational waves**

MS - 2401.09533



Lyth bound $\Delta\varphi \gtrsim \sqrt{\frac{r}{0.002}}$ ⟶ $\Delta\varphi \gtrsim M_P$ **Super-Planckian** field range

Species scale and primordial gravitational waves

EFT consistency $$H \leq \Lambda_s \sim e^{-\lambda \Delta\varphi}$$ Distance Conjecture

↓

$$\lambda = \left| \frac{\Lambda_s'}{\Lambda_s} \right| \leq \frac{1}{\Delta\varphi} \log \frac{M_P}{H}$$

↓

$$\left| \frac{\Lambda_s'}{\Lambda_s} \right| \leq \frac{1}{2\Delta\varphi} \log \frac{10^8}{r}$$

Species scale and **primordial gravitational waves**

MS - 2401.09533

EFT consistency $$H \leq \Lambda_s \sim e^{-\lambda\Delta\varphi}$$ Distance Conjecture

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$$\downarrow$$

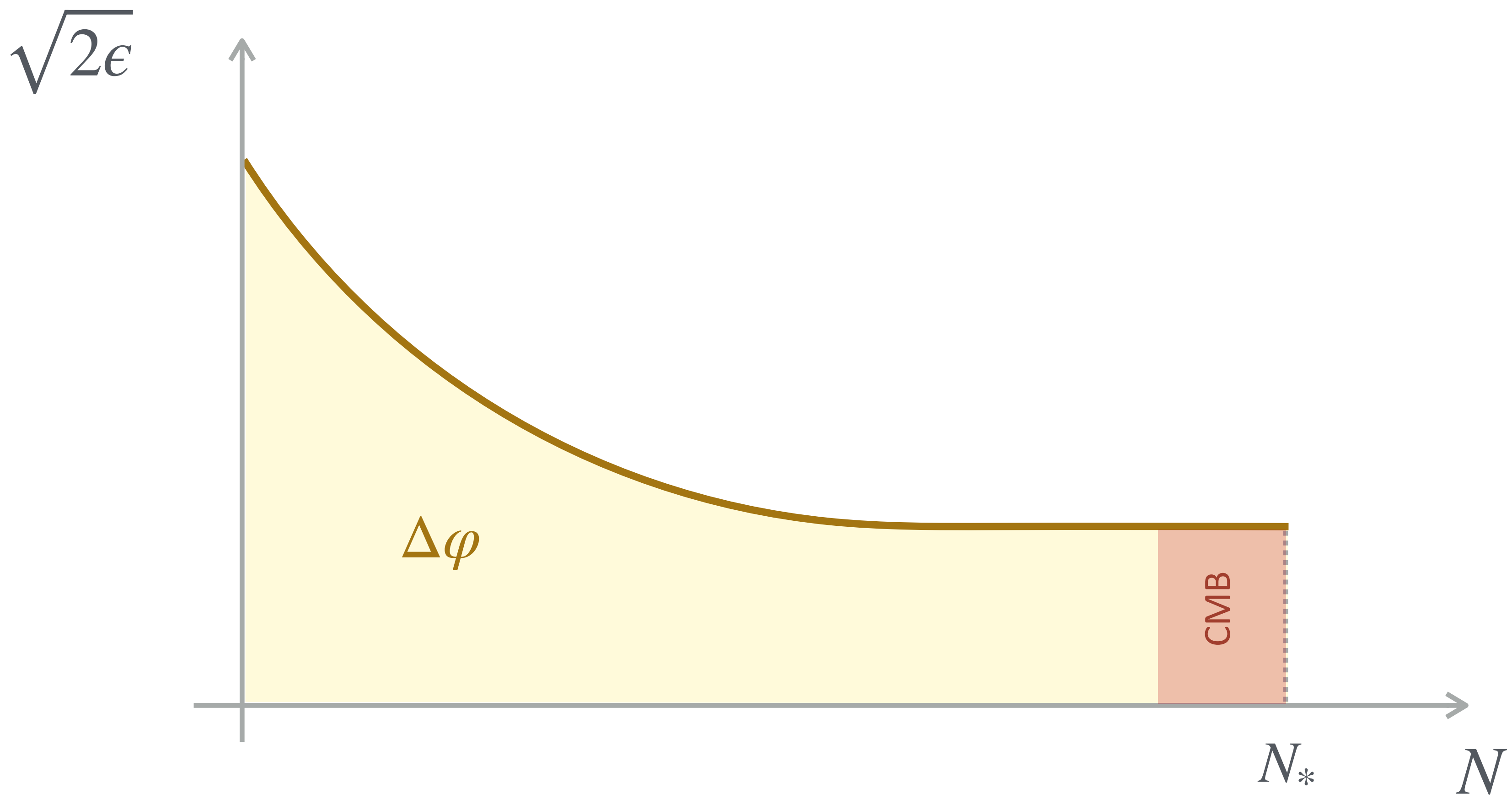
$$\left|\frac{\Lambda_s'}{\Lambda_s}\right| \leq \frac{1}{2\Delta\varphi}\log\frac{10^8}{r}$$

$$\Delta\varphi(r) = \,?$$

Species scale and **primordial gravitational waves**

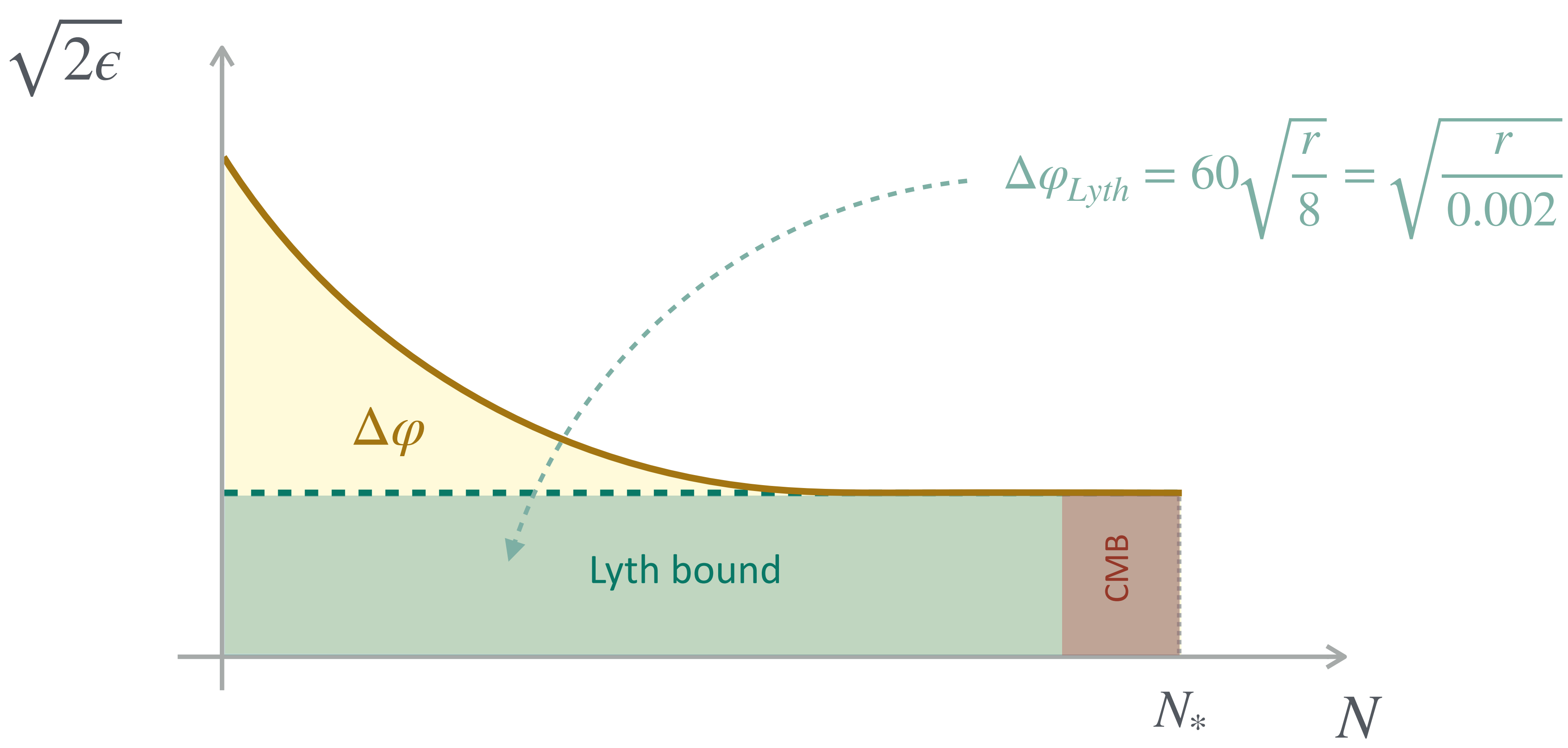
MS - 2401.09533

$$\Delta\varphi = \int \sqrt{2\epsilon}\ \mathrm{d}N$$



Species scale and **primordial gravitational waves**

$$\Delta\varphi = \int \sqrt{2\epsilon}\, \mathrm{d}N$$



Species scale and **primordial gravitational waves**

$$\epsilon(N) = \frac{\beta}{N^p}$$

Species scale and **primordial gravitational waves**

$p = 1$

Monomial *potentials*

$$V(\varphi) \sim \varphi^n$$

$p = 2$

Starobinsky-like *potentials*

$$V(\varphi) \sim \left[1 - e^{-n\varphi} + \ldots\right]$$

$$\epsilon(N) = \frac{\beta}{N^p}$$

$1 < p < 2$

Inverse-hilltop-like *potentials*
(brane inflation)

$$V(\varphi) \sim \left[1 - \left(\frac{\mu}{\varphi}\right)^n + \ldots\right]$$

$p > 2$

Hilltop-like *potentials*

$$V(\varphi) \sim \left[1 - \left(\frac{\varphi}{\mu}\right)^n + \ldots\right]$$

Species scale and **primordial gravitational waves**

$$\epsilon(N) = \frac{\beta}{N^p}$$

$p = 1$

Monomial *potentials*

$$\left|\frac{\Lambda_s'}{\Lambda_s}\right| \lesssim \frac{1}{60\sqrt{2r}} \log \frac{10^8}{r}$$

$p = 2$

Starobinsky-like *potentials*

$$\left|\frac{\Lambda_s'}{\Lambda_s}\right| \lesssim \frac{1}{30\log(60)\sqrt{2r}} \log \frac{10^8}{r}$$

$1 < p < 2$

Inverse-hilltop-like *potentials*
(brane inflation)

$$\left|\frac{\Lambda_s'}{\Lambda_s}\right| \lesssim \frac{1}{(2+n)30\sqrt{2r}} \log \frac{10^8}{r}$$

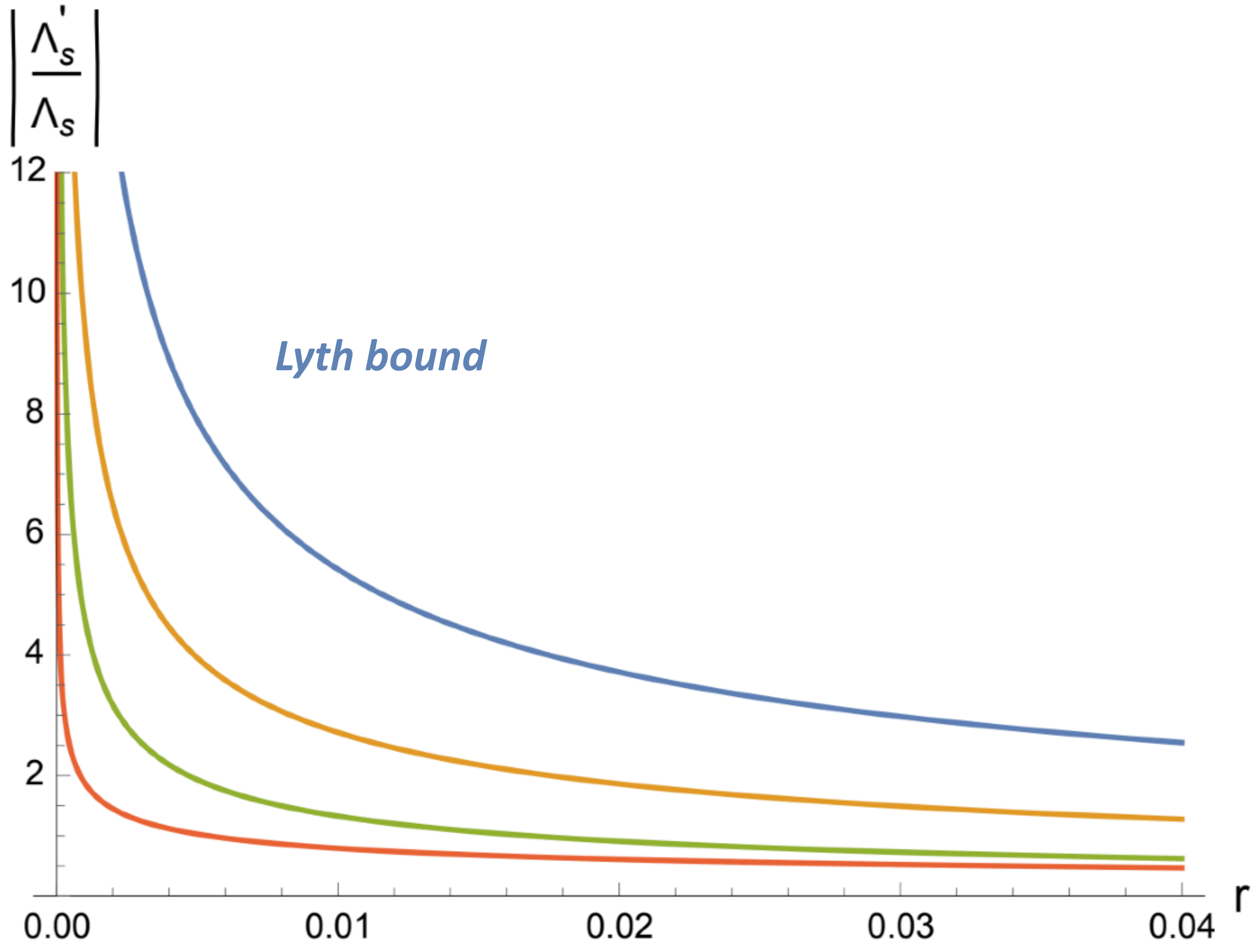
$p > 2$

Hilltop-like *potentials*

$$\left|\frac{\Lambda_s'}{\Lambda_s}\right| \lesssim 2^{\frac{4}{p}-\frac{7}{2}} \frac{p-2}{15} r^{-\frac{1}{p}} \log \frac{10^8}{r}$$

Species scale and **primordial gravitational waves**

MS - 2401.09533



$p = 1$

***Monomial** potentials*

$p = 2$

***Starobinsky-like** potentials*

$p = 3$

***Hilltop-like** potentials*

Species scale and **primordial gravitational waves**

MS - 2401.09533

e.g.

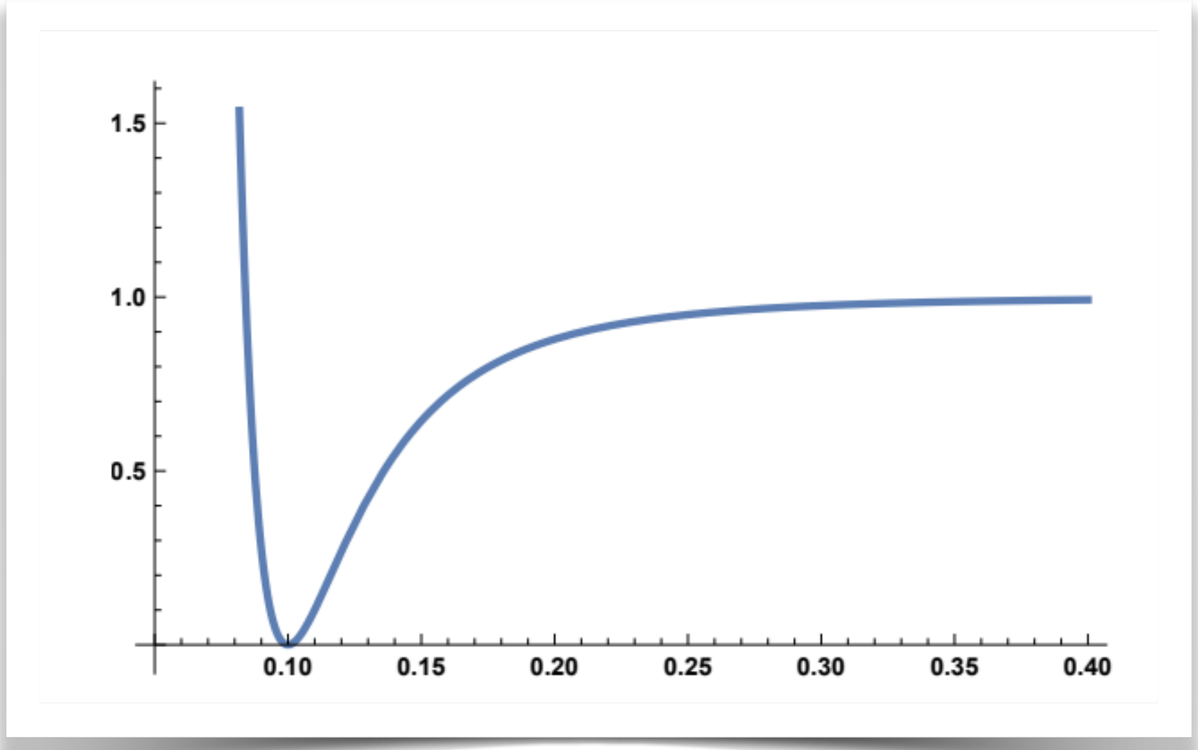
$D3 - \overline{D3}$ **inflation**

Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi 2003
Burgess, Quevedo 2022

$$V(\varphi) \sim \left[1 - \left(\frac{\mu}{\varphi}\right)^4 + \dots\right]$$

$$\left|\frac{\Lambda_s'}{\Lambda_s}\right| \lesssim 0.5$$

$(r \lesssim 0.036)$



plot taken from Burgess, Quevedo 2022

R^2 - **Inflation** and the **species scale**

*Lüst, Masias, Muntz, **MS*** - 2312.13210

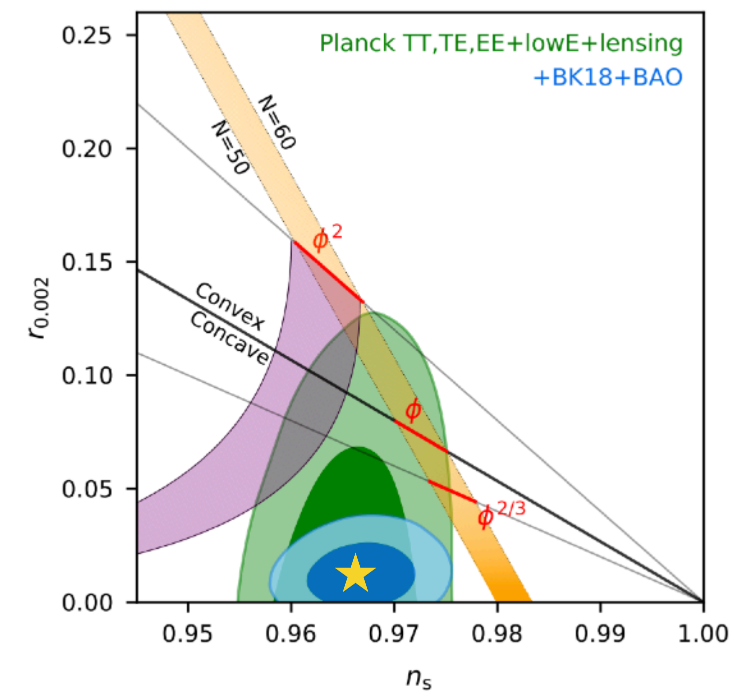
R^2 - **Inflation** and the **species scale**

*Lüst, Masias, Muntz, **MS*** - 2312.13210

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} \left(R + \frac{R^2}{M^2} \right) \right]$$

Starobisky 1980

Starobisky 1984



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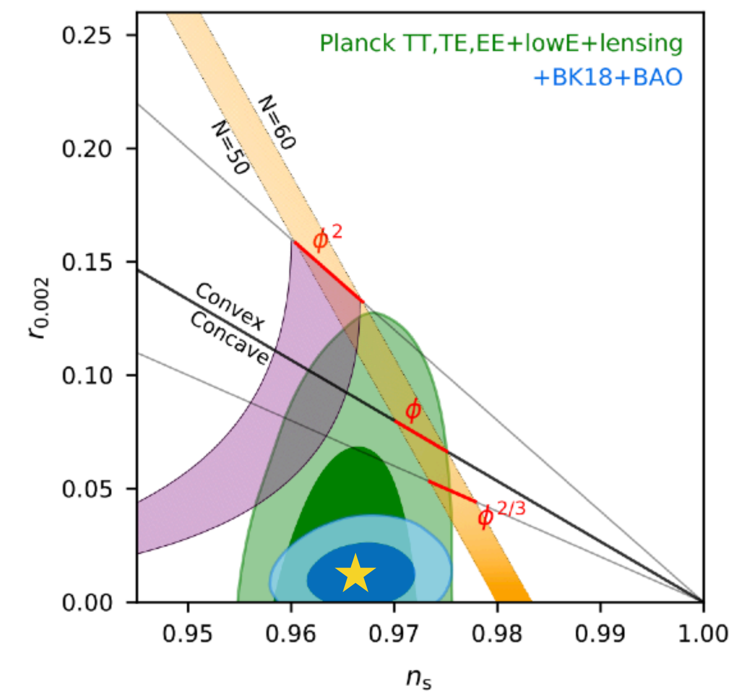

$$M = 10^{14}\ \text{GeV}$$

fixed by **CMB observation**

$$M = ?$$

origin?

"Quantum loop corrections to Einstein field equation"
Starobinsky 1980

R^2 - **Inflation** and the **species scale**

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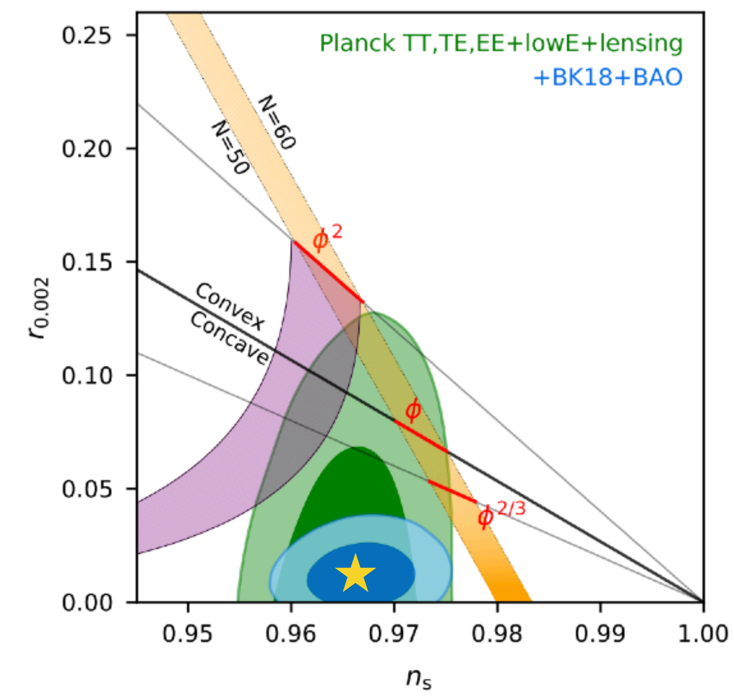

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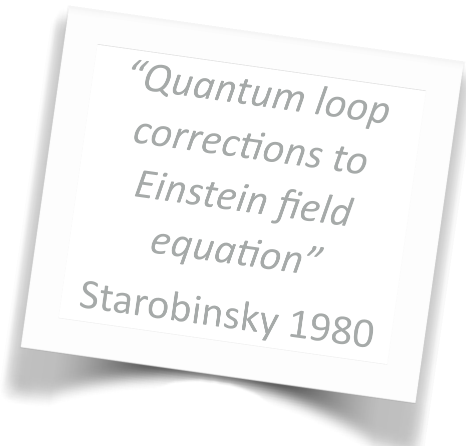
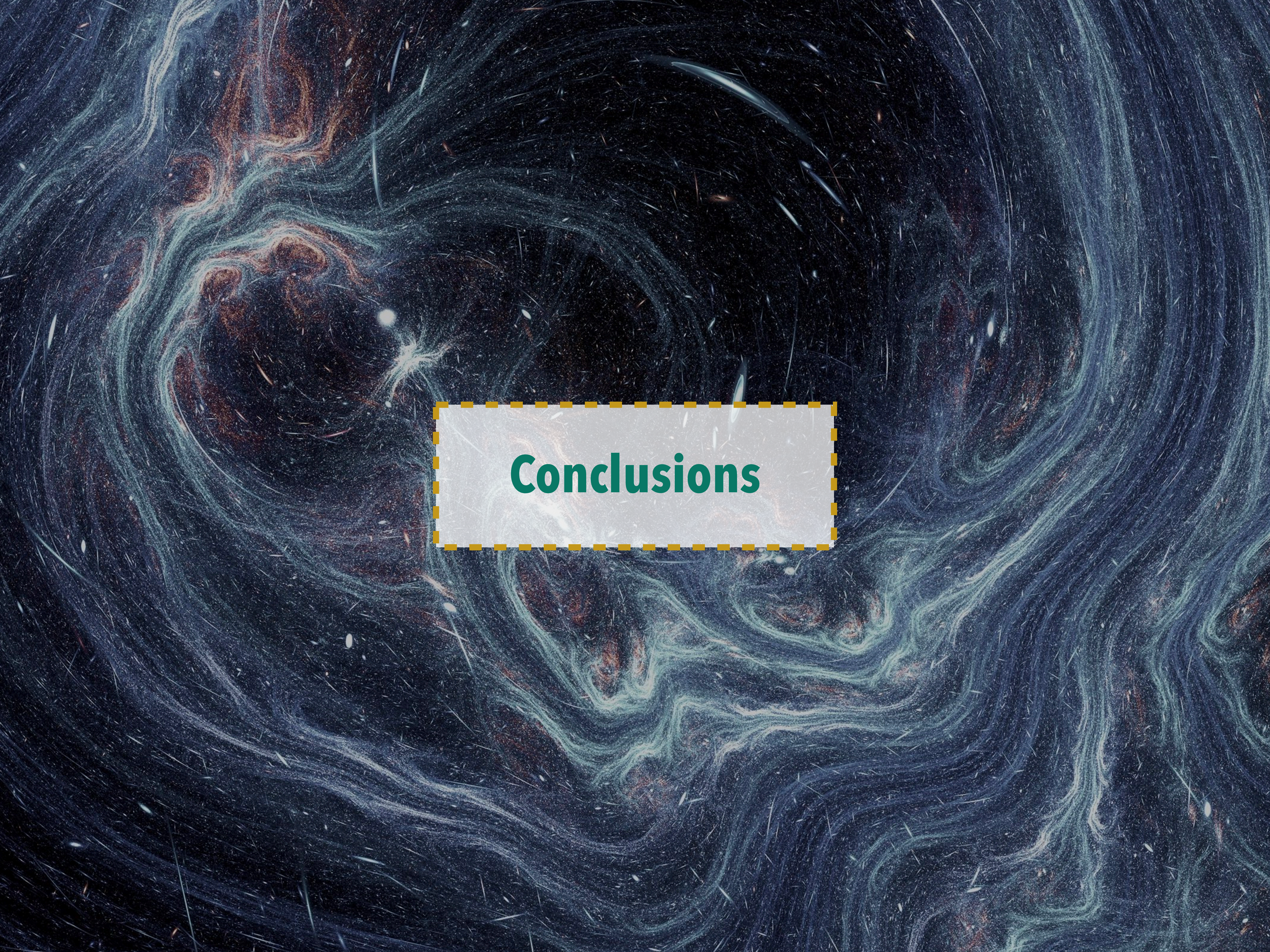


we argue

$$M \simeq \Lambda_s$$

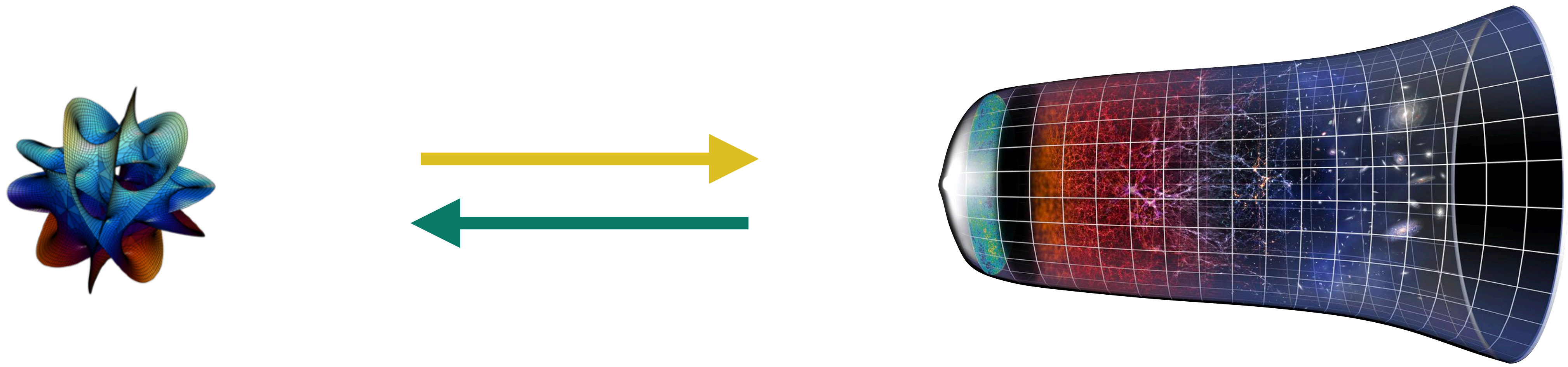
originated by **quantum effects** of **towers** of light **species**

see Joaquin Masias' talk!

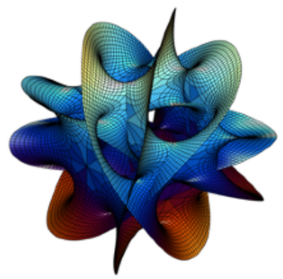


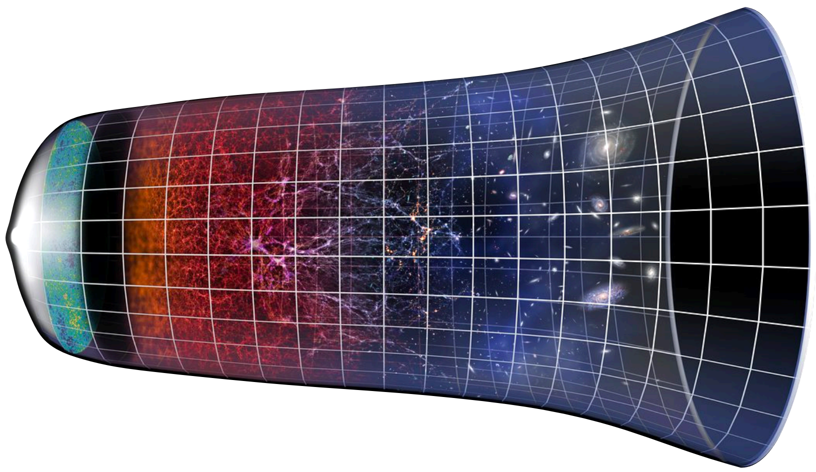
Conclusions

Conclusions



Conclusions





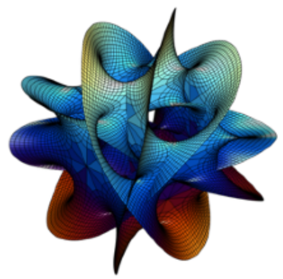
1

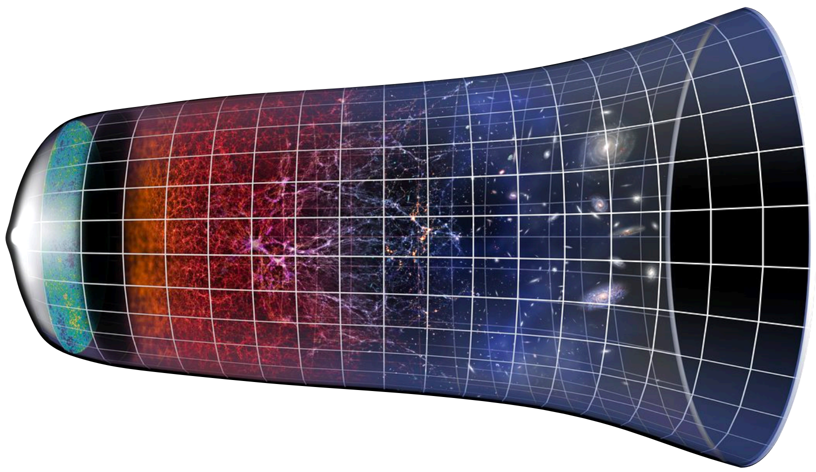
Towers of species lead to a **renormalization** of the **quantum gravity cut-off**

$$\Lambda_{QG} = \frac{M_P}{N^{\frac{1}{d-2}}}$$

Dvali 2007

Conclusions





1

Towers of species lead to a **renormalization** of the **quantum gravity cut-off**

$$\Lambda_{\mathrm{QG}} = \frac{M_{\mathrm{P}}}{N^{\frac{1}{d-2}}}$$

Dvali 2007

2

Universal **upper bound on** the scalar **field range**

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

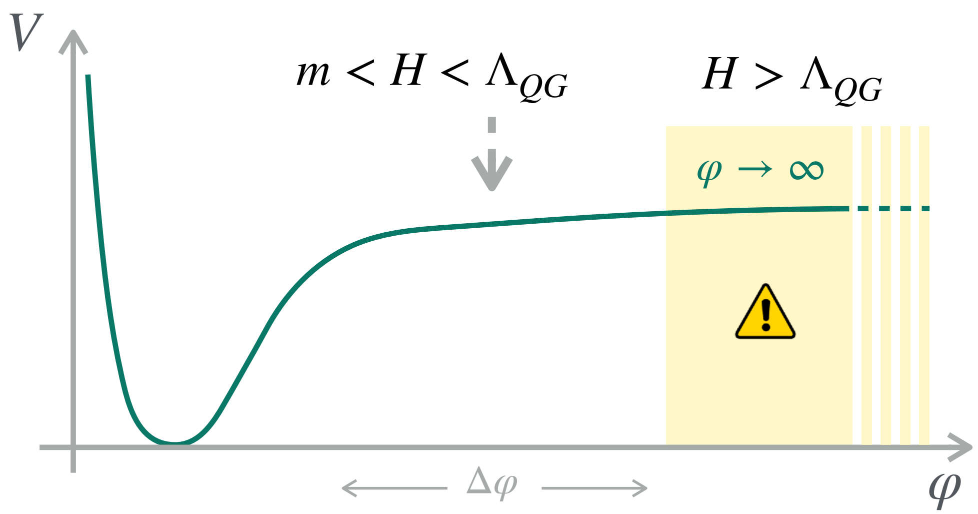
MS, Valenzuela 2018

MS 2019

Conclusions

3

Effects of species
on **inflationary observables**



$$\delta\{n_s, r, f_{NL}\} \propto \left(\frac{H}{\Lambda_{\mathrm{QG}}}\right)^{2+p}$$

Lüst, Masias, Pieroni, MS - work in progress

Conclusions

3

Effects of species
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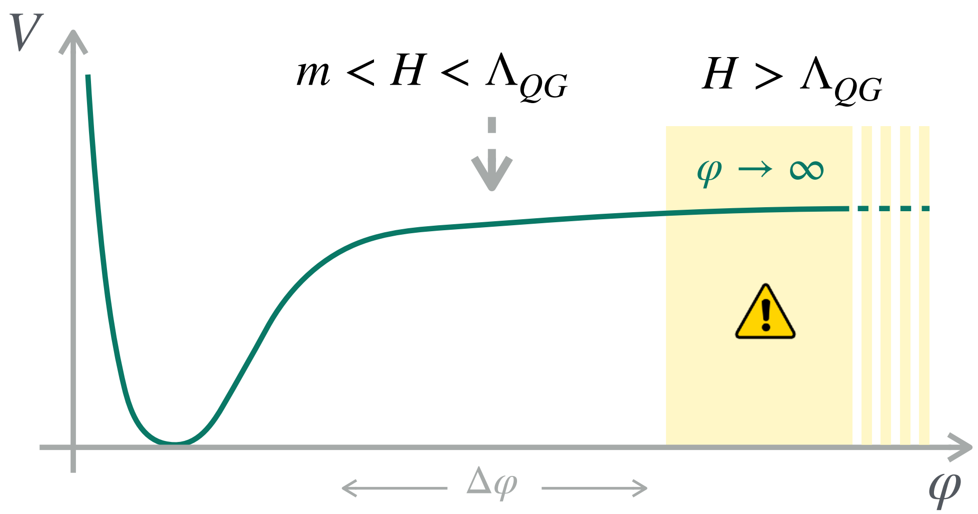

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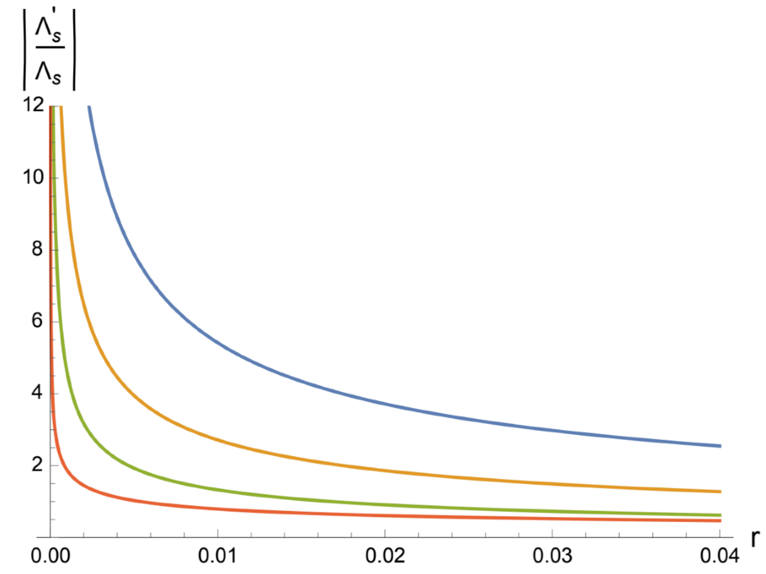
Lüst, Masias, Pieroni, MS - work in progress

4

Detection of **PGWs** sets **upper bound** on **decay rate of** $\Lambda_{\rm QG}$



$$\left|\frac{\Lambda'_{\rm QG}}{\Lambda_{\rm QG}}\right| \lesssim \frac{c}{\sqrt{r}} \log\frac{10^8}{r}$$

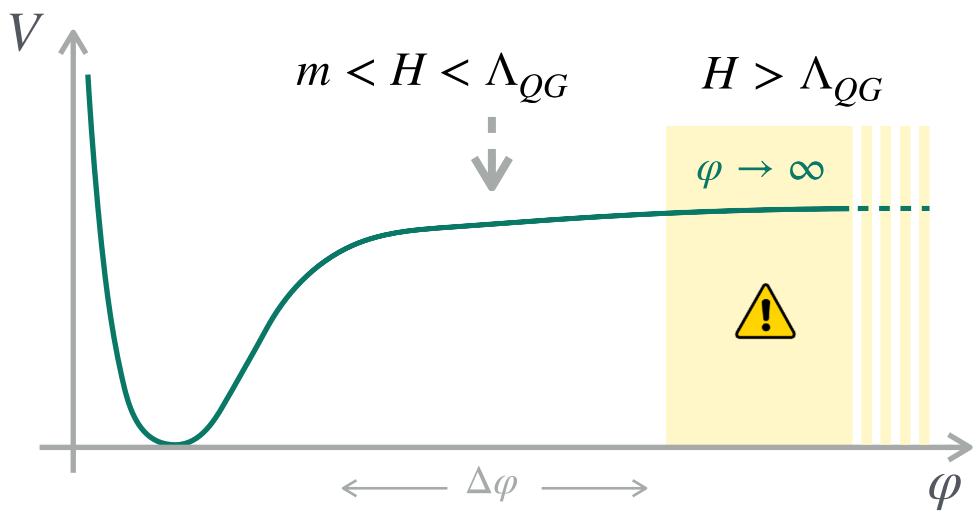
MS 2024

Conclusions

thanks!

3

Effects of species on **inflationary observables**



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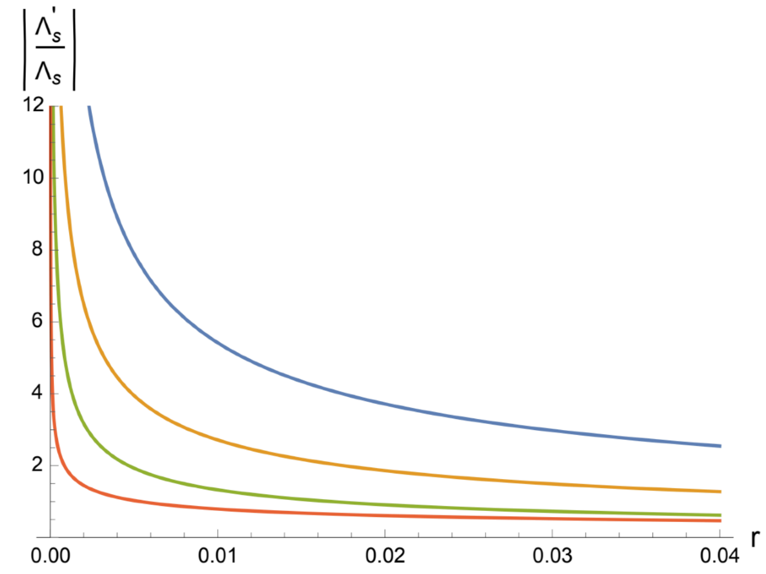


$$\left|\frac{\Lambda'_{\rm QG}}{\Lambda_{\rm QG}}\right| \lesssim \frac{c}{\sqrt{r}} \log\frac{10^8}{r}$$

MS 2024

Extra-slides

R^2 - **Inflation** and the **species scale**

Lüst, Masias, Muntz, MS - 2312.13210

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} \left(R + \frac{R^2}{M^2} \right) \right]$$

we argue

$$M \simeq \Lambda_s$$

originated by **quantum effects** of **towers** of light **species**

- **Calculation of the graviton propagator contribution**

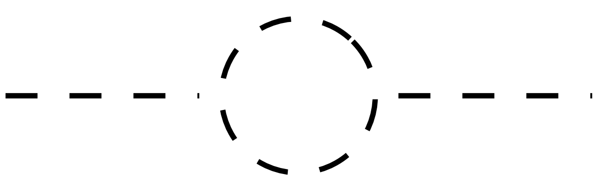
$R + \mathcal{O}\left(R^2\right)$

$$\pi(p^2) \simeq \left(p^2 - \frac{2a}{M^2} p^4 \right)^{-1}$$

$\longleftrightarrow$

R + tower of species

$$\pi(p^2) \simeq \left(p^2 - \frac{1}{\Lambda_s^2} p^4 \right)^{-1}$$



Consequences on inflationary EFT

- **Energy scale**

$M \simeq \Lambda_s$ but also $M \simeq H$ → $\Lambda_s \simeq H$

(in the Starobinsky model)

boundary of the **EFT validity**

R^2 - **Inflation** and the **species scale**

Lüst, Masias, Muntz, MS - 2312.13210

Consequences on inflationary EFT

- **Energy scale**

$$M \simeq \Lambda_s \quad \text{but also} \quad M \simeq H \longrightarrow \boxed{\Lambda_s \simeq H}$$

boundary of the **EFT validity**

- **KK modes**

$$M \simeq \Lambda_s \simeq 10^{14}\ \text{GeV} \longrightarrow N_s \simeq 10^{10} \longrightarrow \boxed{m_{kk} \simeq 10^4\ \text{GeV}}$$

10 orders below H

Consequences on inflationary EFT

- Cosmology constrains **Species Scale decay rate**

$$\Lambda_s = M_* \, e^{-\gamma\phi} \quad \longrightarrow \quad V(\phi) = \frac{M_*^2 \, M_P^2}{8} e^{-2\gamma\phi} \left(1 - e^{-\sqrt{\frac{2}{3}}\phi/M_P}\right)^2$$

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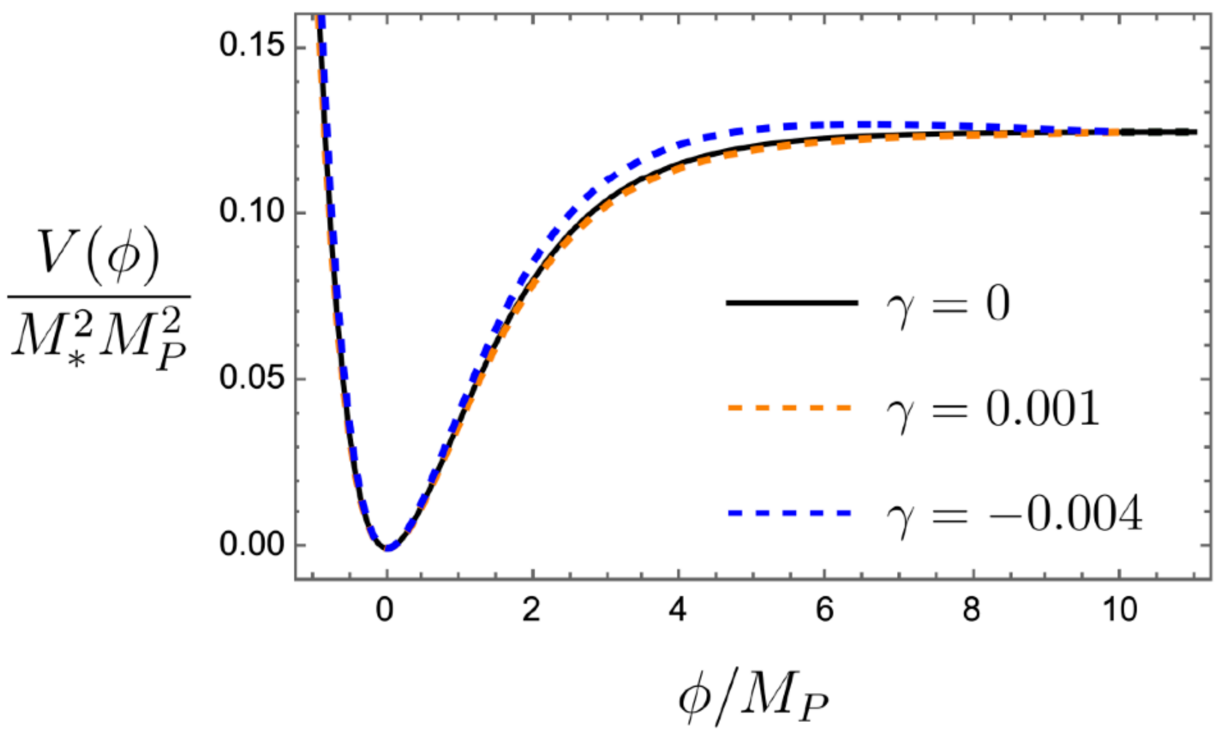

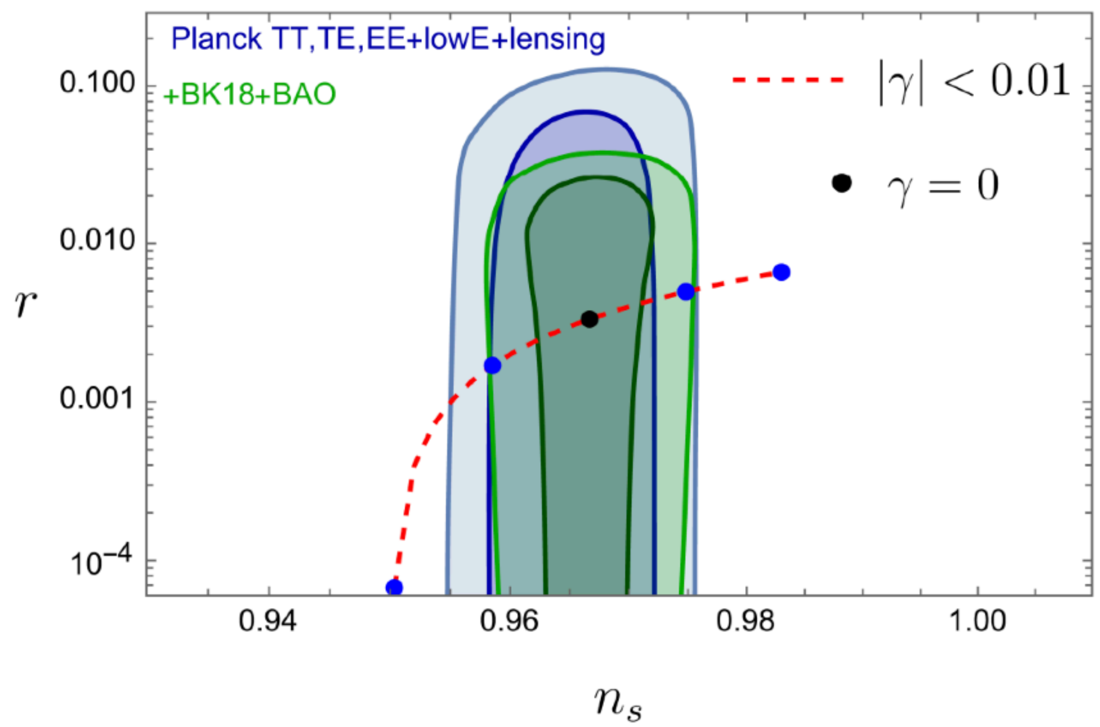

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$$n_s - 1 \simeq -\frac{2}{N_e} - 2\gamma\sqrt{\frac{2}{3}} + \mathcal{O}(\gamma^2)$$

$$r \simeq \frac{12}{N_e^2} - \gamma\frac{8\sqrt{6}}{N_e} + \mathcal{O}(\gamma^2)$$

CMB data →

$$-0.001 \leq \gamma \leq 0.004$$

⚠ too small

$$|\gamma| \geq \frac{1}{\sqrt{(d-1)(d-2)}} = \frac{1}{\sqrt{6}}$$