Title: More Axions from Strings

Speakers: Marco Gorghetto

Series: Particle Physics

Date: September 11, 2020 - 1:00 PM

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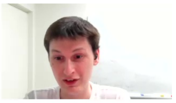
Abstract: The axion solution to the strong CP problem also provides a natural dark matter candidate. If the Peccei-Quinn symmetry has ever been restored after inflation, topological defects of the axion field would have formed and produced relic axions, whose abundance is in principle calculable. We study the contribution to the abundance produced by string defects during the so-called scaling regime. Clear evidence of scaling violations is found, the most conservative extrapolation of which strongly suggests a large number of axions from strings. The overall result is a lower bound on the QCD axion mass in the post-inflationary scenario that is substantially stronger than the naive one from misalignment.



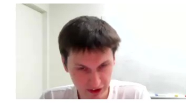
More Axions from Strings

Marco Gorghetto

WEIZMANN INSTITUTE OF SCIENCE

with **E.Hardy** and **G.Villadoro**

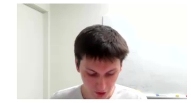
[1806.04677 + 2007.04990]



Outline

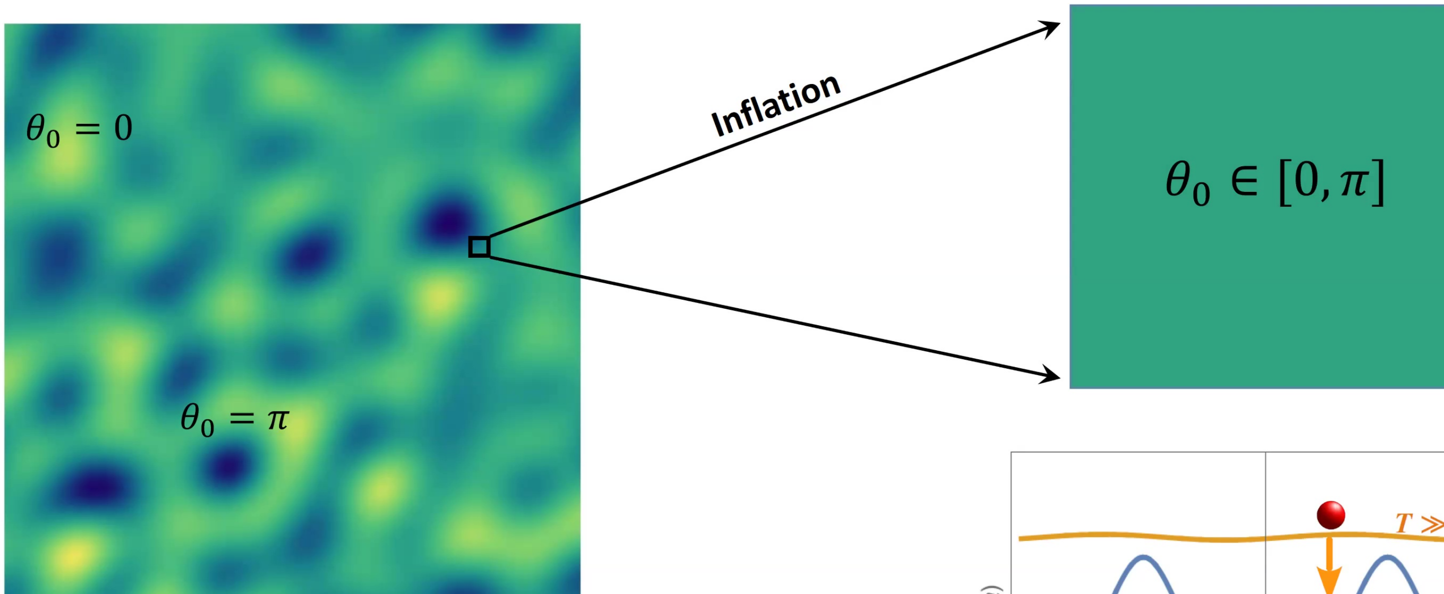
- Axion Cosmology and String Dynamics
- Reconstruction of the Scaling Solution
- Implications for the QCD Axion mass

Axion Cosmology

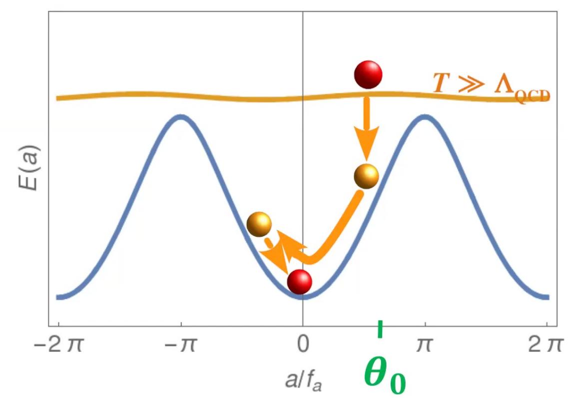


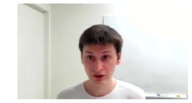
Pre-inflationary:

$f_a \gtrsim \max(H_I, T_R)$



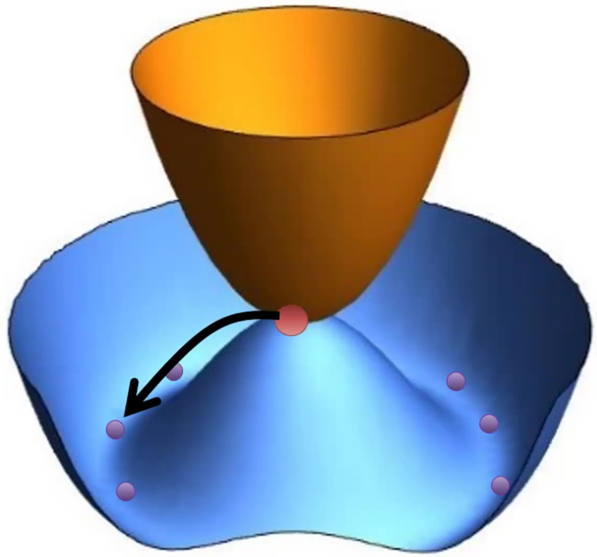
$$\Omega_a \approx 0.1\theta_0^2 \left[\frac{f_a}{10^{12}\mathrm{GeV}}\right]^{1+\epsilon}$$





The PQ Phase Transition

$T \gtrsim f_a$

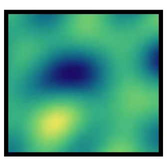


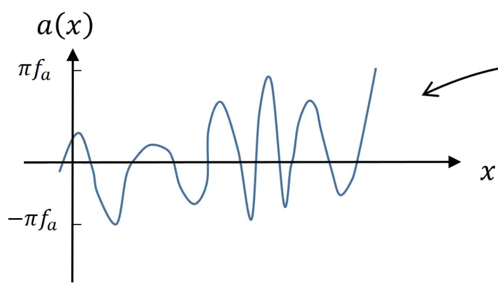
$$\phi = |\phi| e^{i\frac{a}{f_a}}$$

$T \lesssim f_a$

Similarly if:

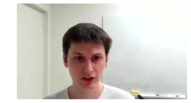
$H_I \gtrsim f_a$

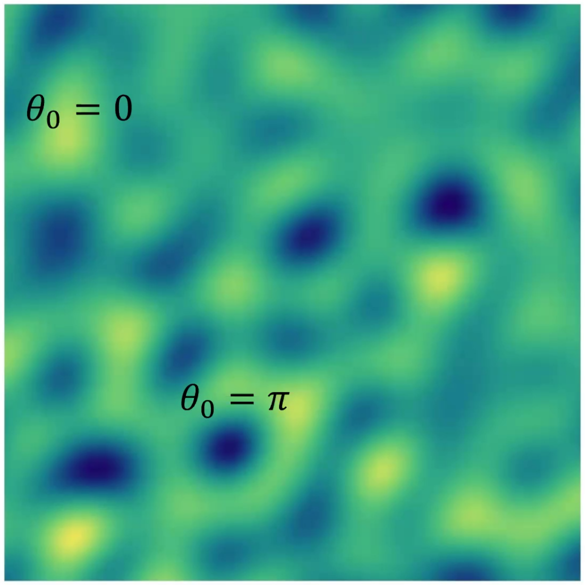




after PQ breaking axion field has random fluctuations within the Hubble horizon

The Post-Inflationary scenario





Post-inflationary:

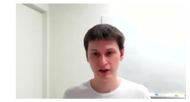
$$f_a \lesssim \max(H_I, T_R)$$

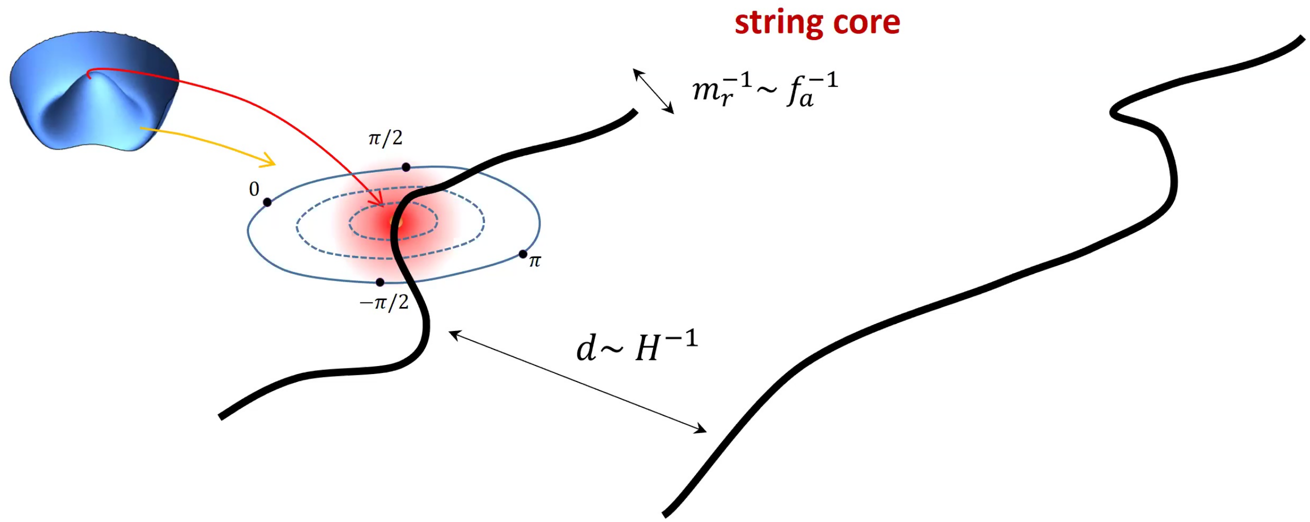
no free parameters in the initial conditions

$$\boldsymbol{\Omega_a = \Omega_a}(f_a) \overset{!}{=} \boldsymbol{\Omega_{DM}}$$

prediction for f_a!

Axion Strings





string tension

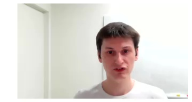
$$\mu = \frac{E}{L} \sim \underbrace{\pi f_a^2}_{\text{core}} \underbrace{\log \frac{d}{m_r^{-1}}}_{\text{axion gradient}} \sim \pi f_a^2 \log \frac{m_r}{H}$$

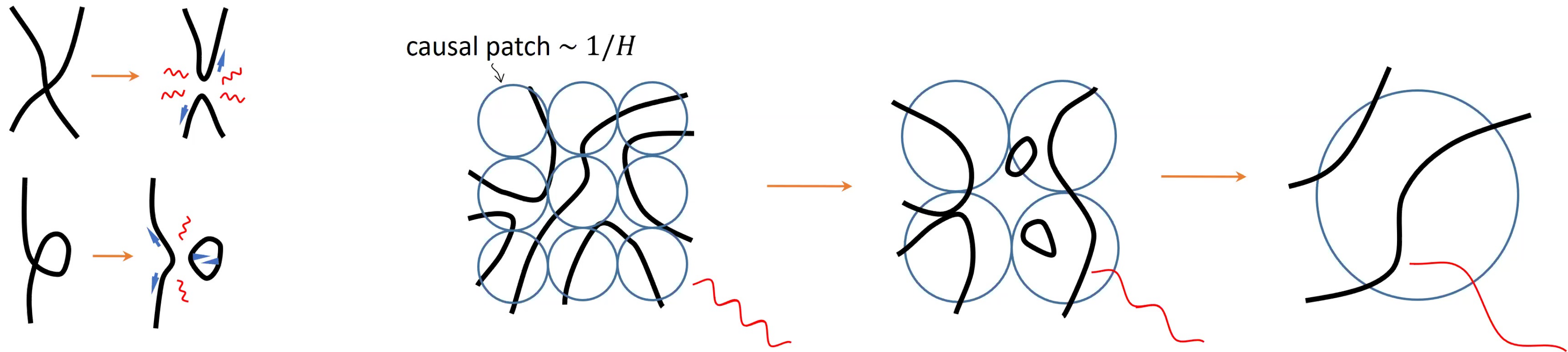
core

axion gradient

Grows logarithmically in time

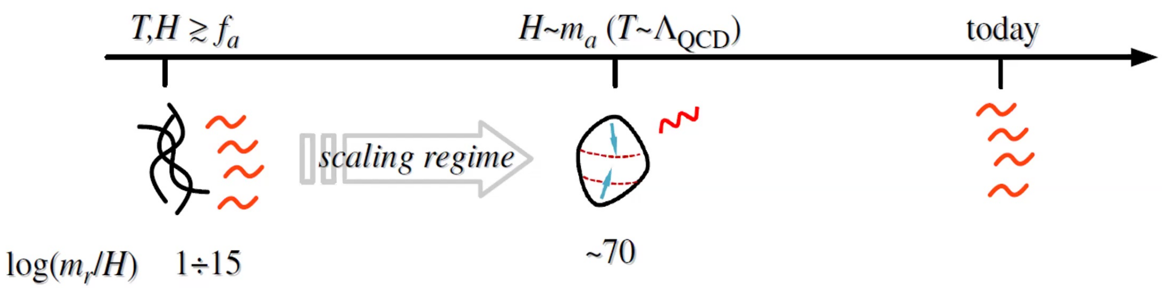
The Scaling Regime





$$\frac{d\rho_a}{dt} \simeq \frac{\xi \mu}{t^3}$$

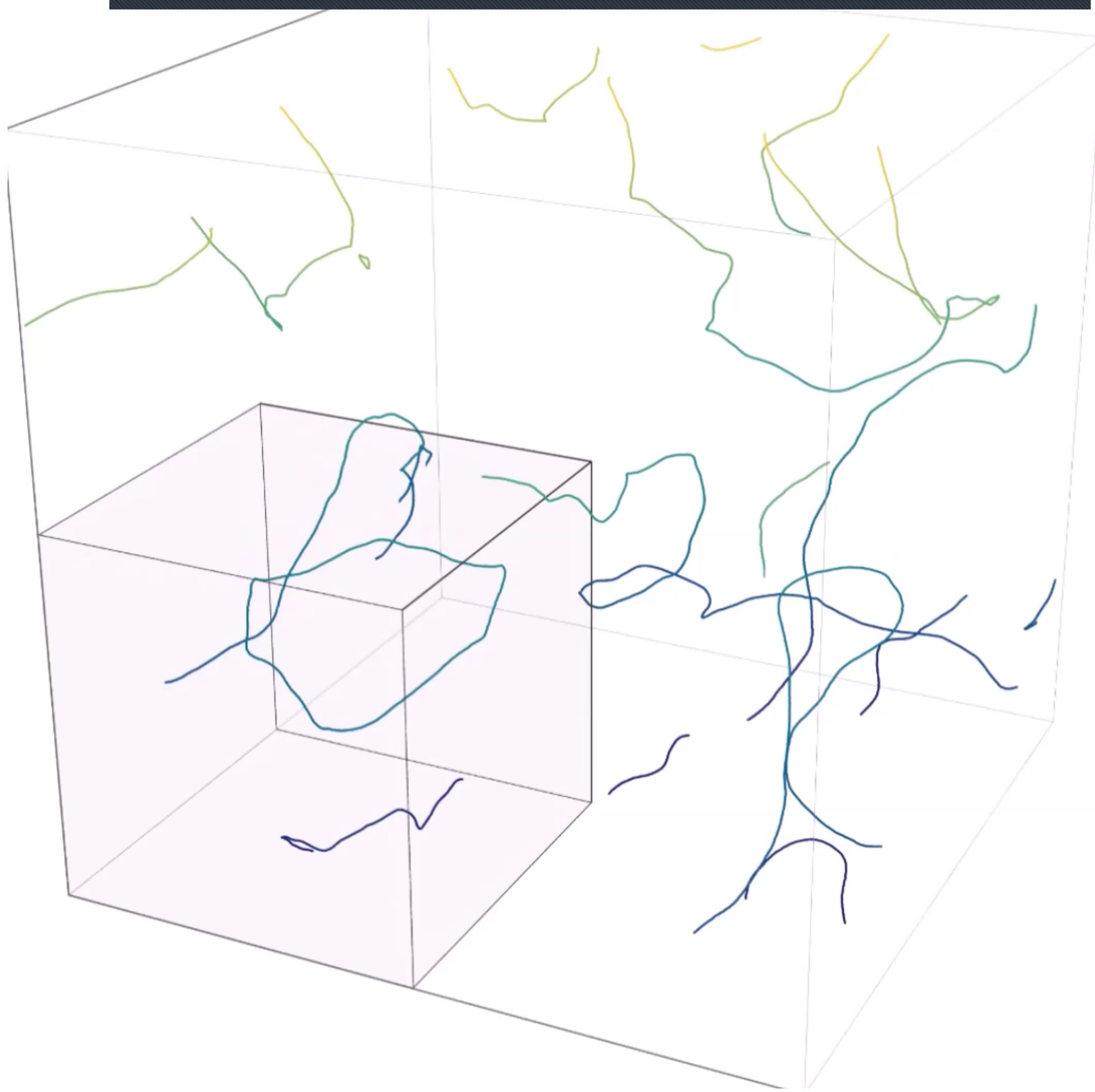
number of strings

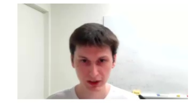


strings form

domain walls form and annihilate

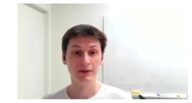
relic axions



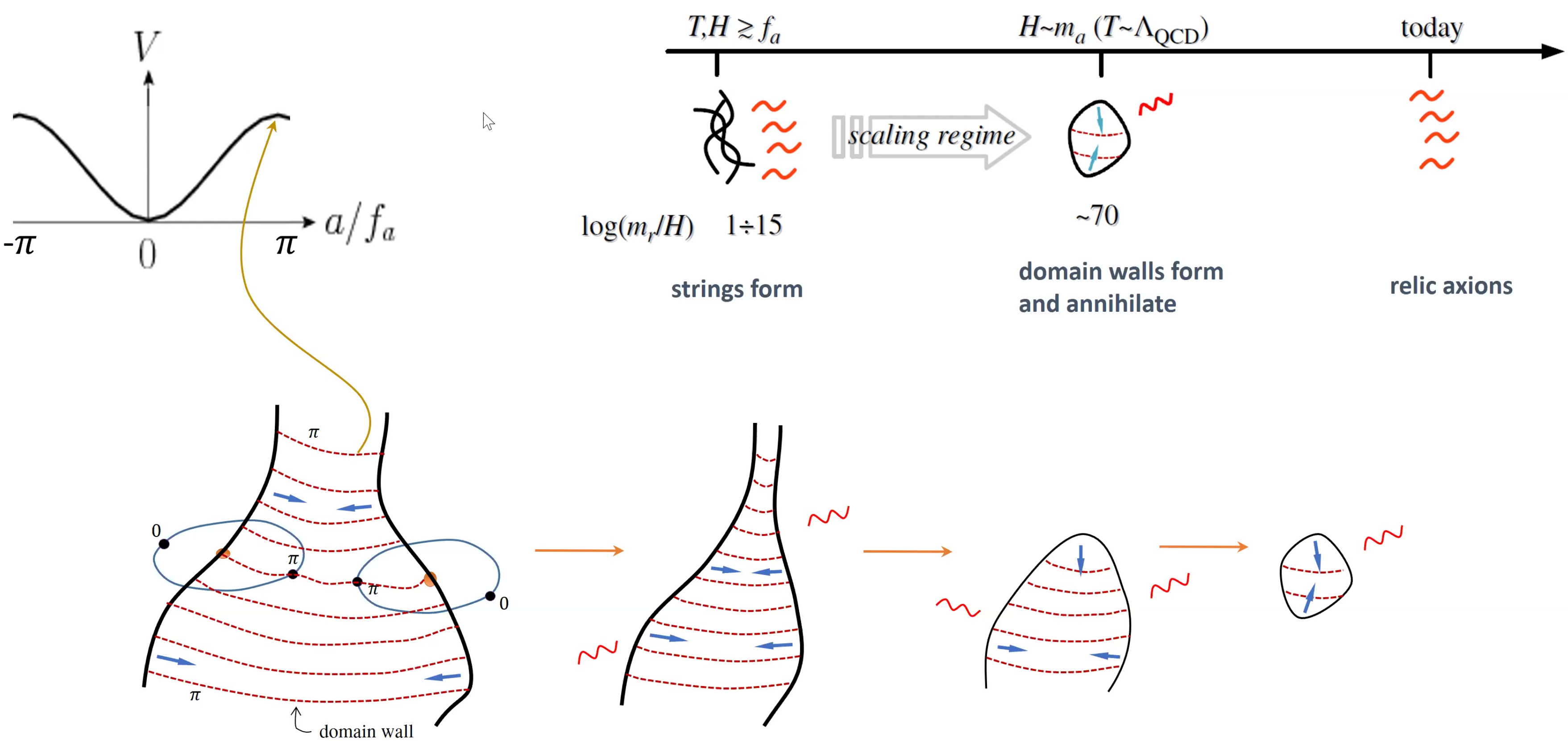


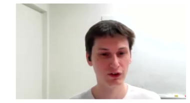
$$\mathcal{L} = |\partial_\mu \phi|^2 - \frac{m_r^2}{2v^2}\left(|\phi|^2 - \frac{v^2}{2}\right)^2$$

Axion Domain Walls



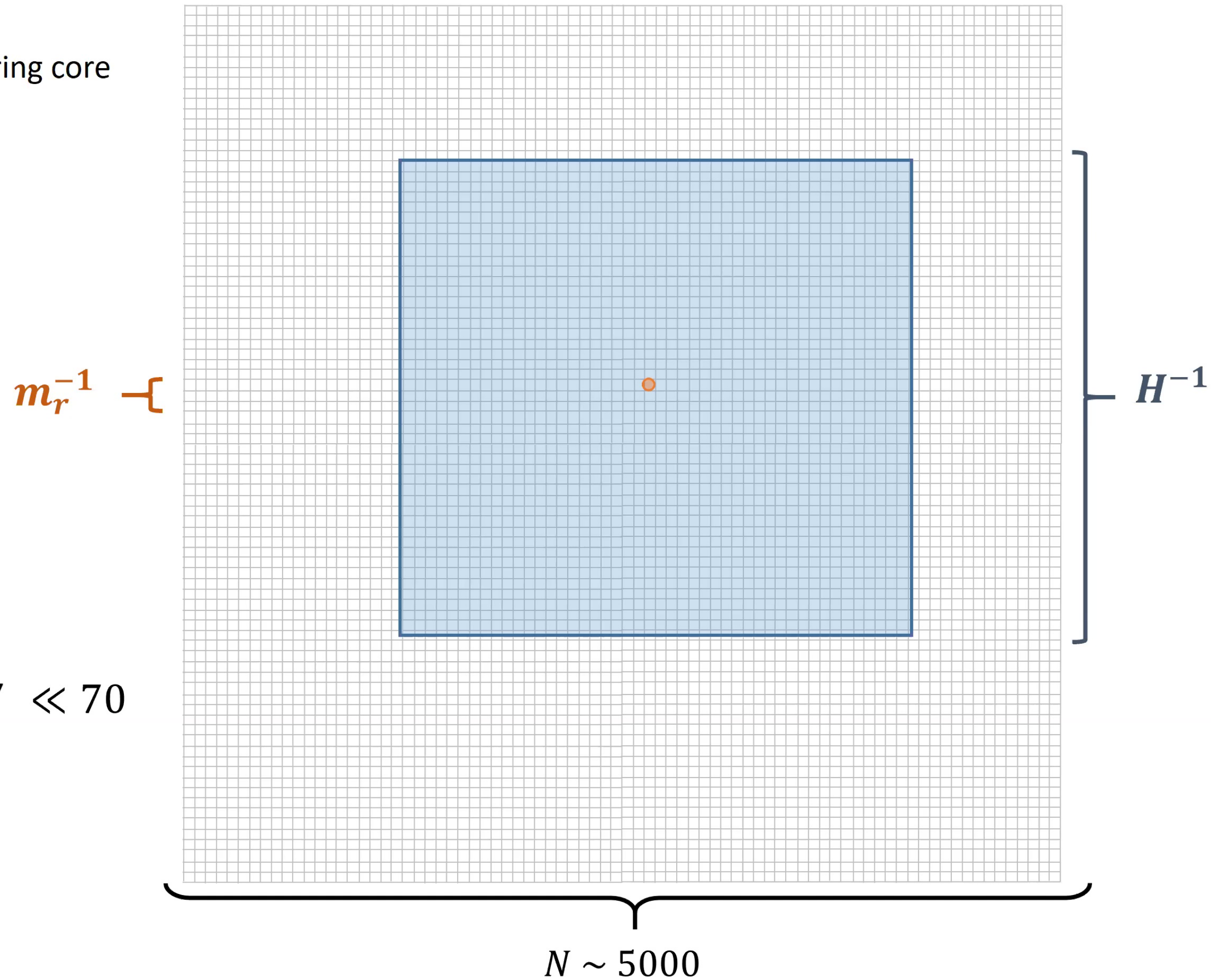
@ $H \sim m_a$ ($T \sim \Lambda_{QCD}$)





The Bottle Neck

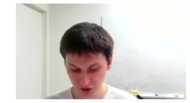
- a few lattice points per string core
- a few Hubble patches

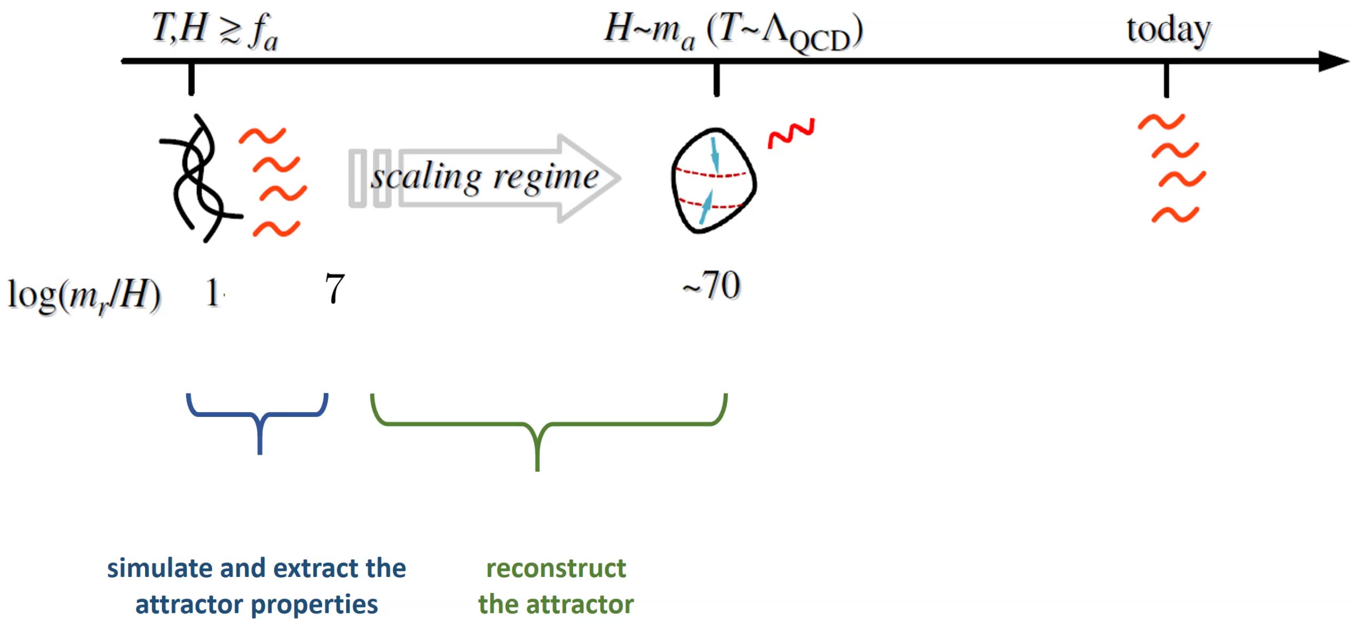


$$\log\frac{m_r}{H} \leq \log\left(\frac{\square}{\bigcirc}\right) \sim 7 \ll 70$$

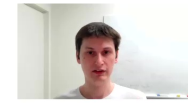
[redacted]

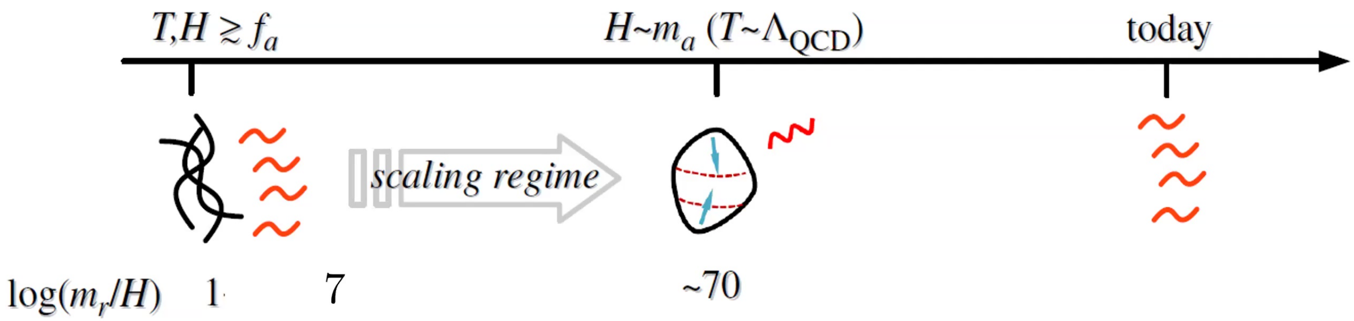
A Less Ambitious Goal: a Lower Bound





A Les[redacted]nd





1) **Energy in axions:**

$$\frac{d\rho_a}{dt} \simeq \frac{\xi\mu}{t^3}$$

number of strings

2) **Axion number density:**

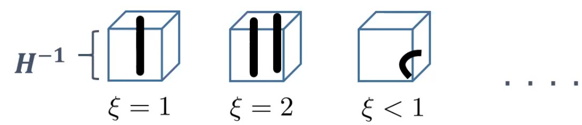
$$n_a = \int \frac{dk}{\omega_k}\frac{\partial\rho_a}{\partial k}$$

axion energy density spectrum

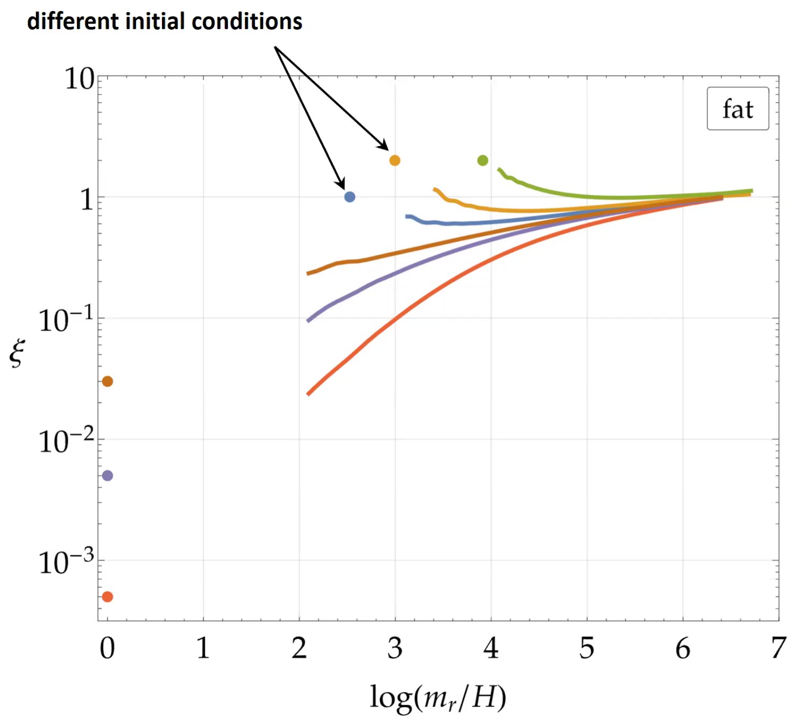
3) **Axion number density through the axion potential turn on**

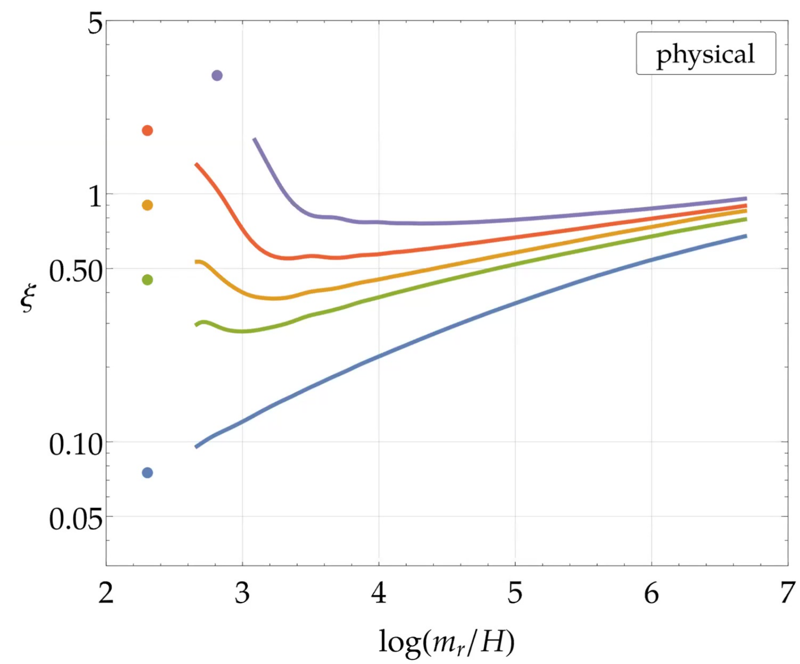
1) The [redacted]

$$\xi \equiv \frac{N_{\text{strings}}}{H^{-3}}$$

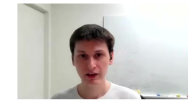


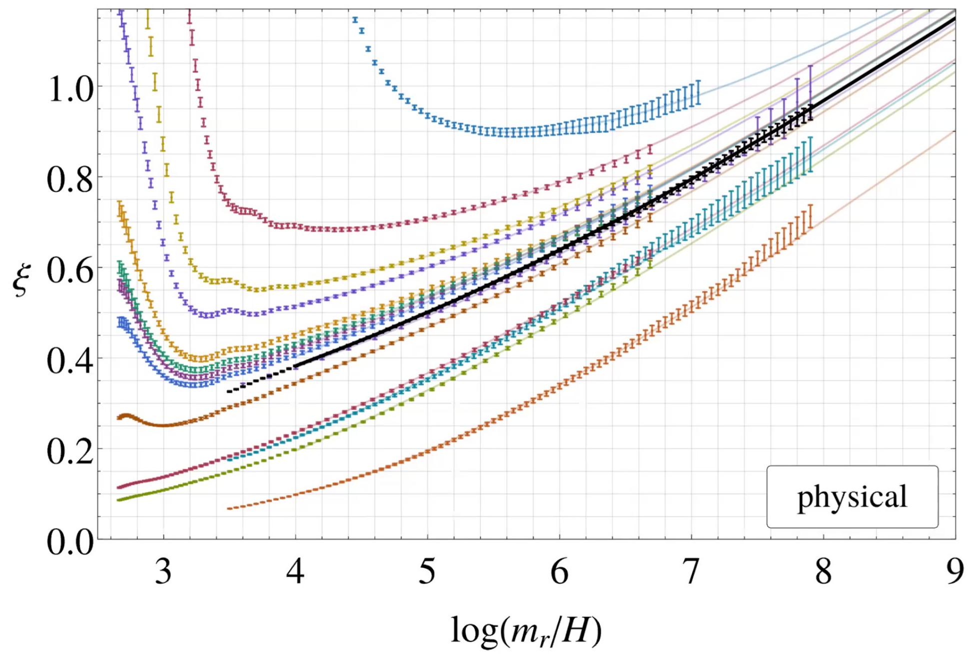
string length in one Hubble volume in units of H^{-1}

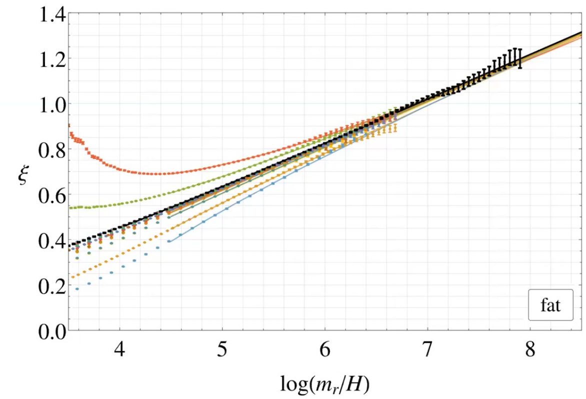




Logarithmic Running



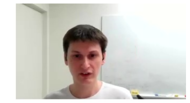




Scaling Violation

$$\xi = c_1 \log + c_0 + \frac{c_{-1}}{\log} + \frac{c_{-2}}{\log^2}$$

$$\xi \xrightarrow{\log \to 70} 15(2)$$

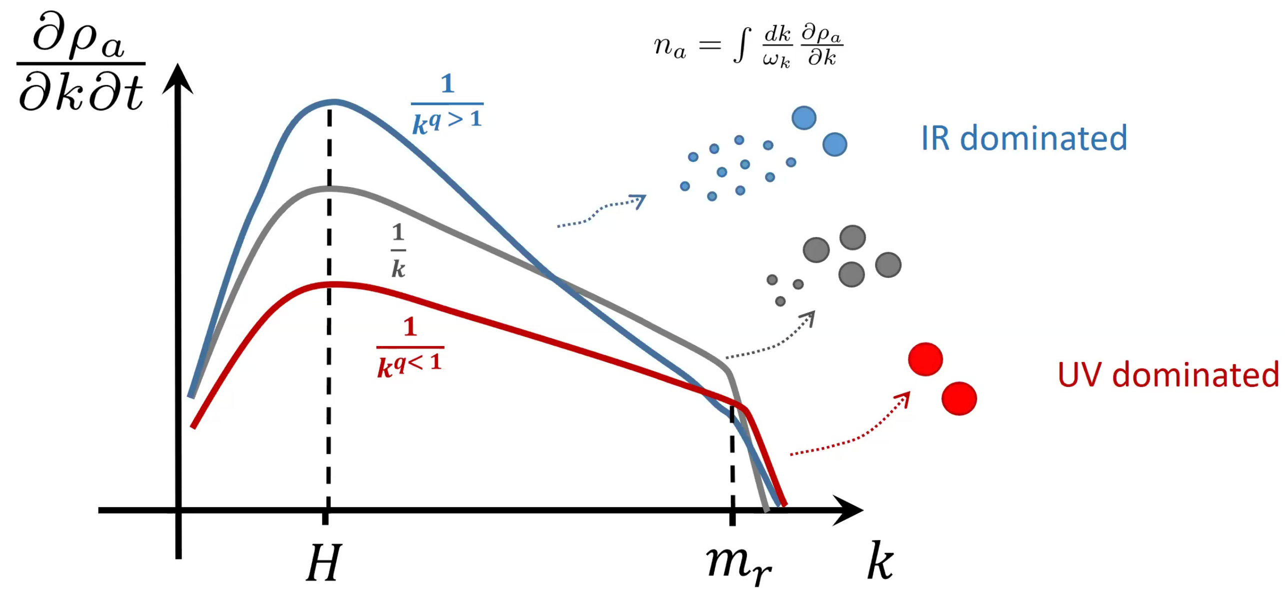


2) The Axion Spectrum

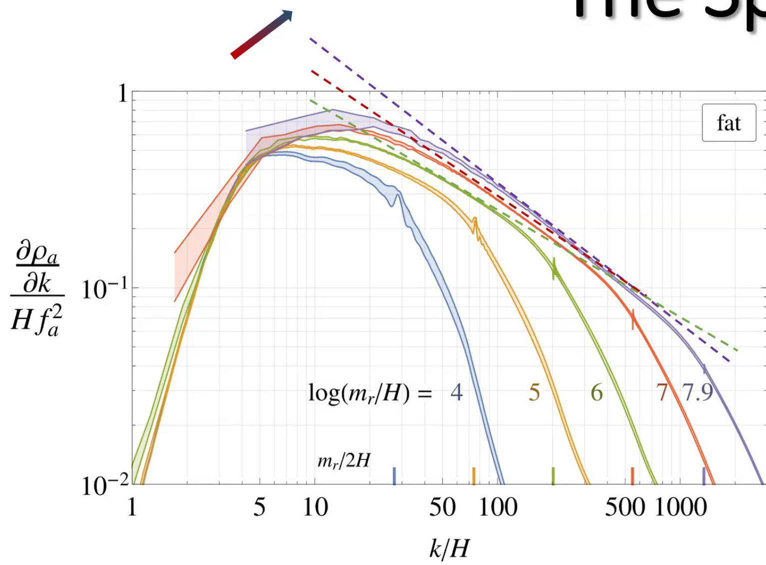
$$\frac{\partial \rho_a}{\partial k \partial t} \equiv \text{energy spectrum of axions emitted}$$

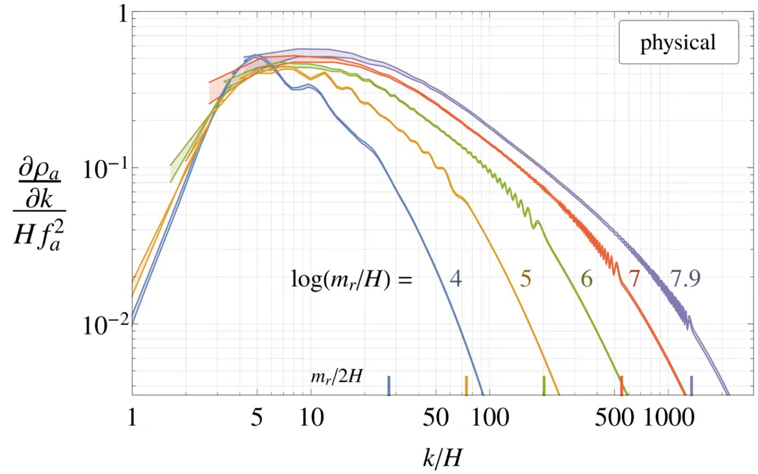
Theoretical expectation

- natural cut-offs at H and m_r
- peak at H because strings have curvature of $O(H)$
- in between an approximate power law: $\frac{\partial \rho_a}{\partial k \partial t} \propto \frac{1}{k^q}$
- in principle q could be time-dependent, $q = q(\log)$



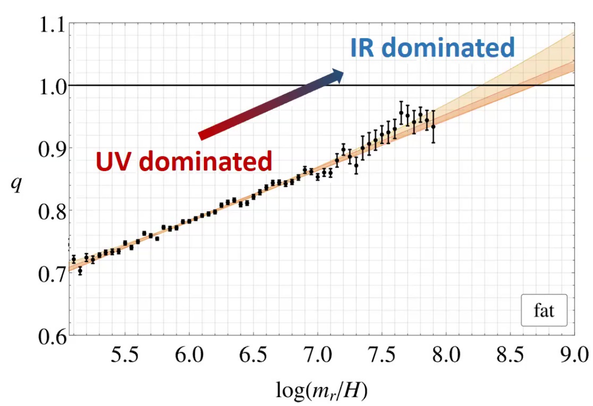
The Spectral Index

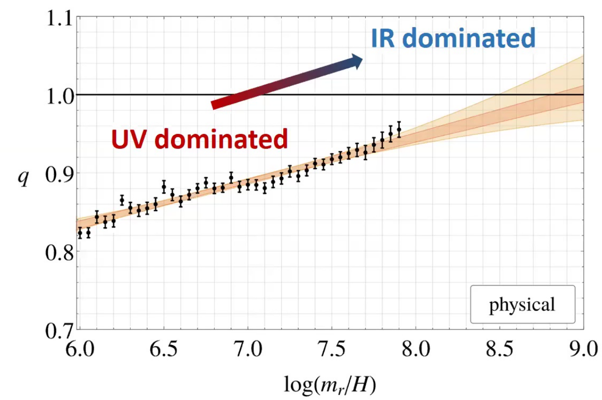


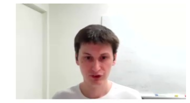


Running of q

log → 70
$q > 1$

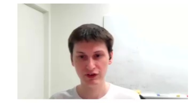






[redacted]

3) Number density after the nonlinear regime

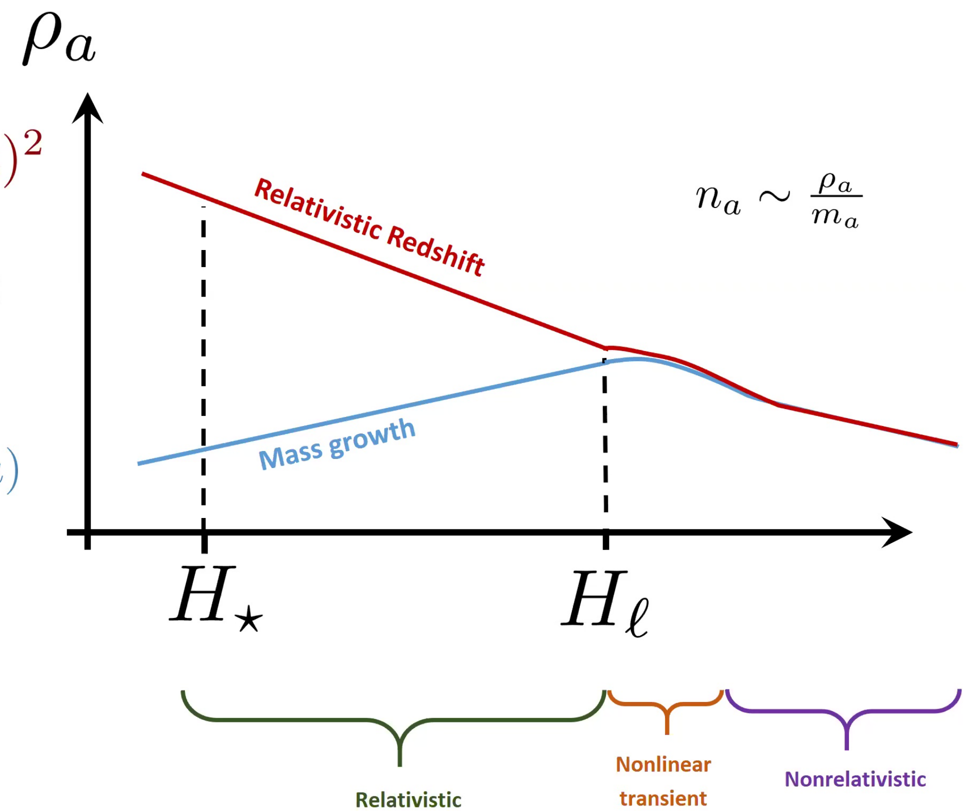


$@\ H = m_a \equiv H_\star$

$$\frac{\xi\mu}{t^2} \sim 10^3 \left[\frac{\xi \log}{10^3}\right] H^2 f_a^2 \sim \quad (\nabla a)^2$$

$$@\ H_\star \quad \gg$$

$$m_a^2 f_a^2 \sim \quad V(a)$$



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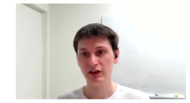
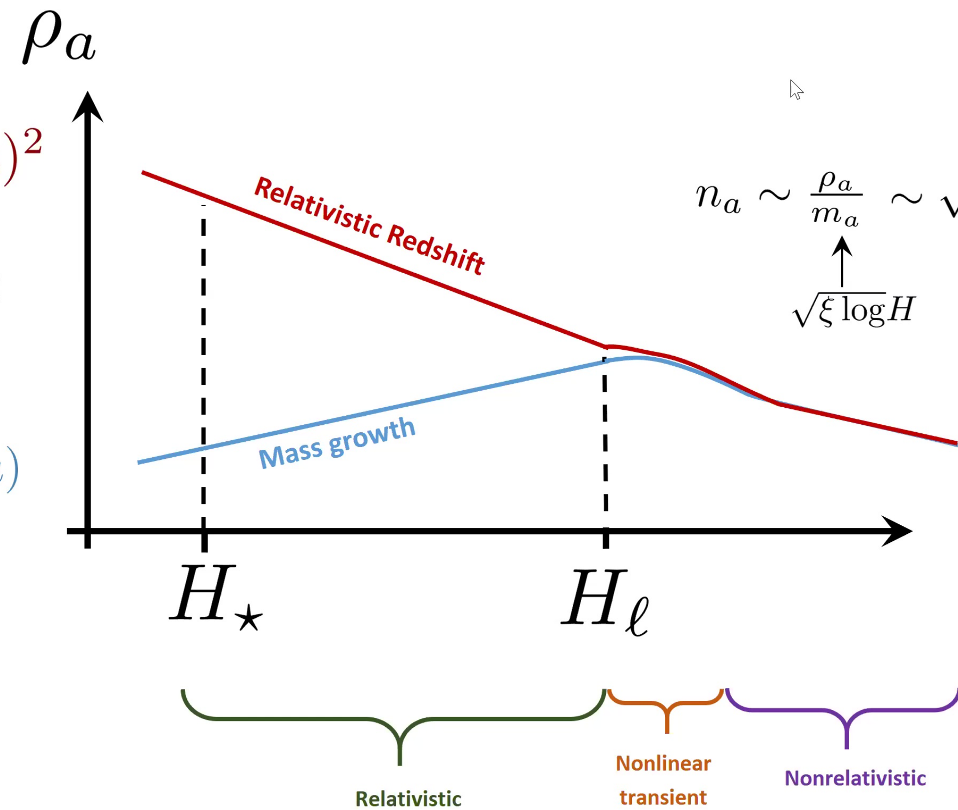


$@\ H = m_a \equiv H_\star$

$$\frac{\xi\mu}{t^2} \sim 10^3 \left[\frac{\xi \log}{10^3}\right] H^2 f_a^2 \sim \quad (\nabla a)^2$$

$@\ H_\star$ $\gg$

$$m_a^2 f_a^2 \sim \quad V(a)$$

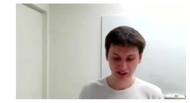


$$n_a \sim \frac{\rho_a}{m_a} \sim \sqrt{\xi \log} H f_a^2$$

$\uparrow$

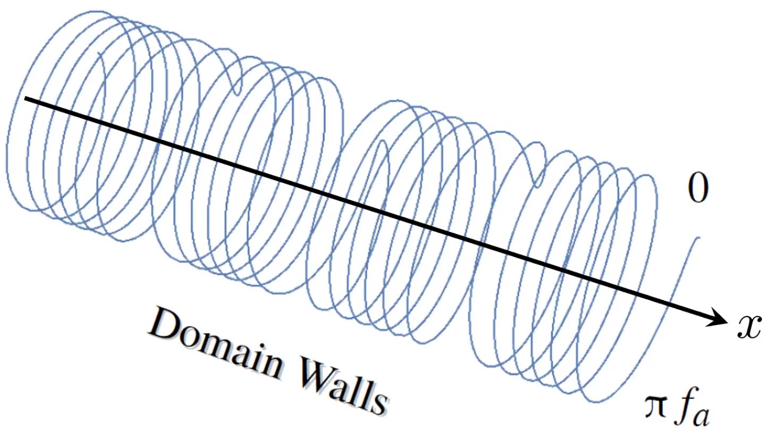
$\sqrt{\xi \log} H$

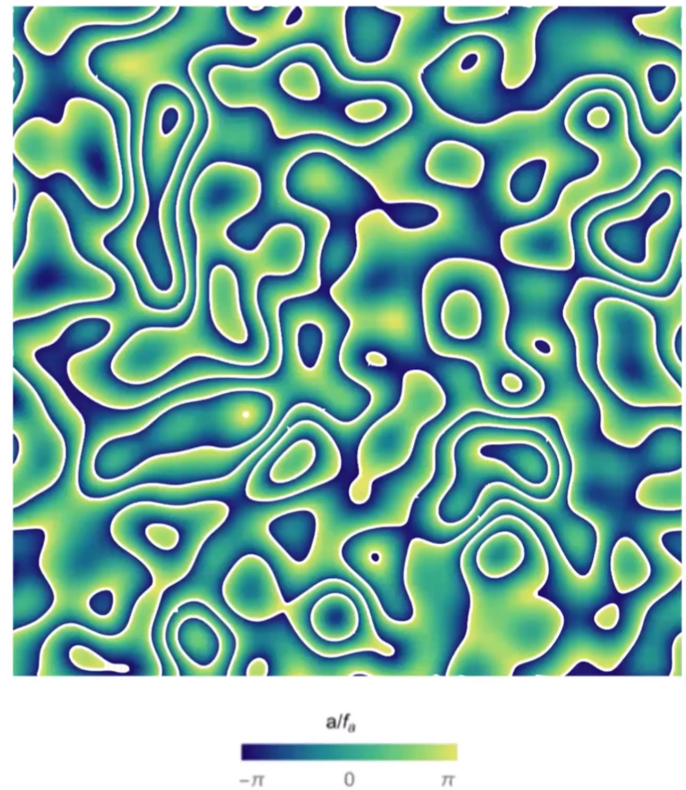
More Domain Walls



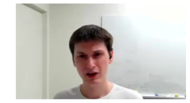
@ $H_\star$

$$\rho_a \sim (\nabla a)^2 \sim H^2 a^2 \;\; \sim \xi \log H^2 f_a^2 \;\; \Rightarrow \;\; \frac{a}{2\pi f_a} \sim \sqrt{\xi \log} = O(10)$$





More Domain Walls



@ $H_\star$

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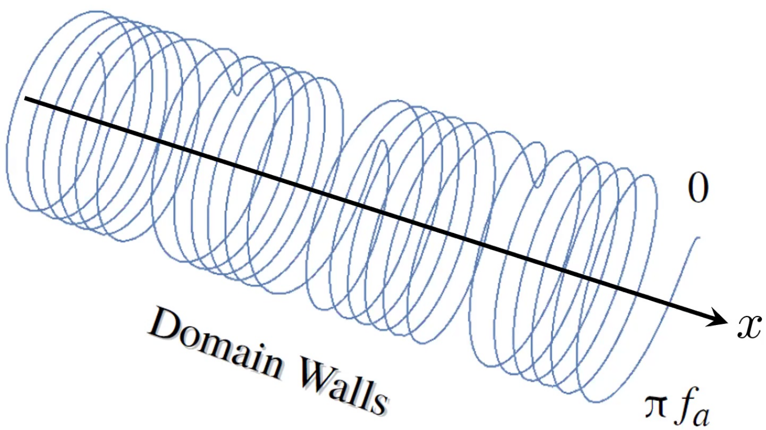
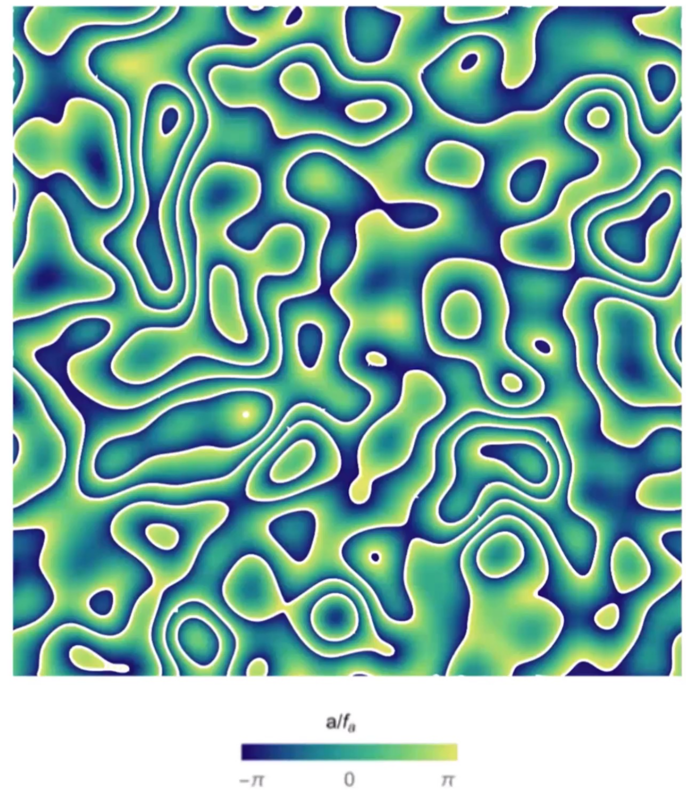
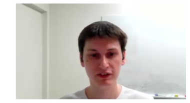


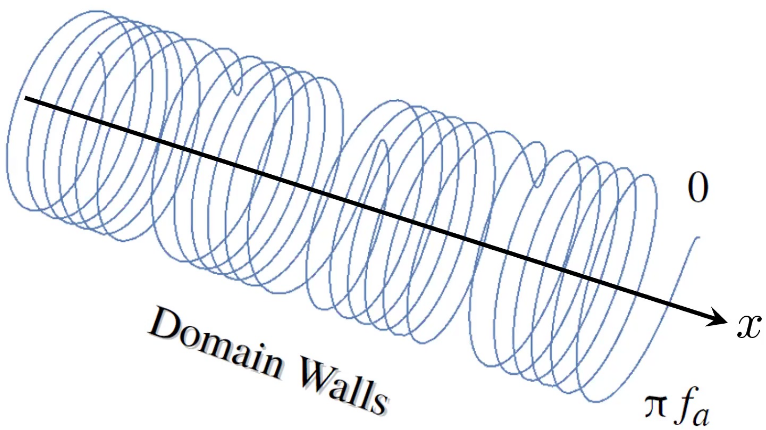


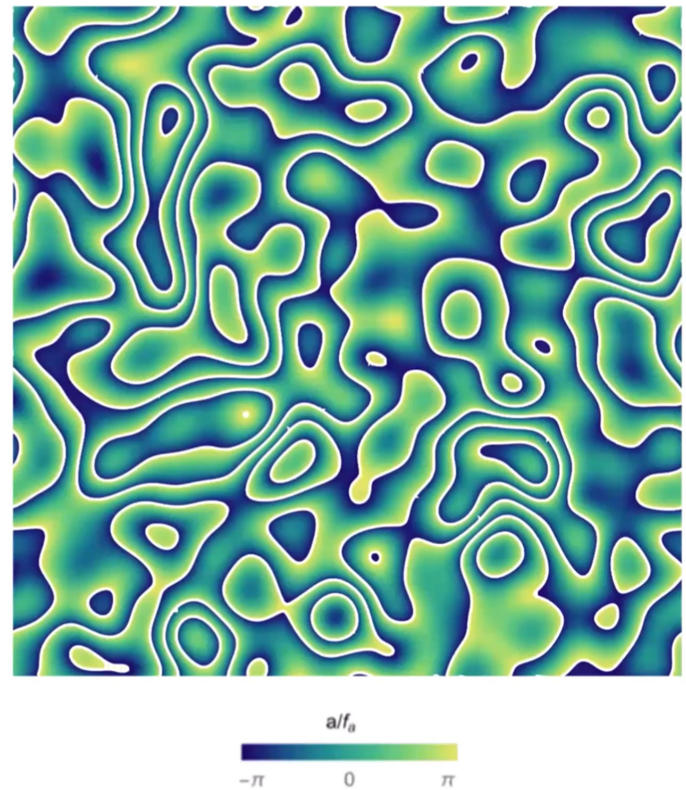


More Domain Walls

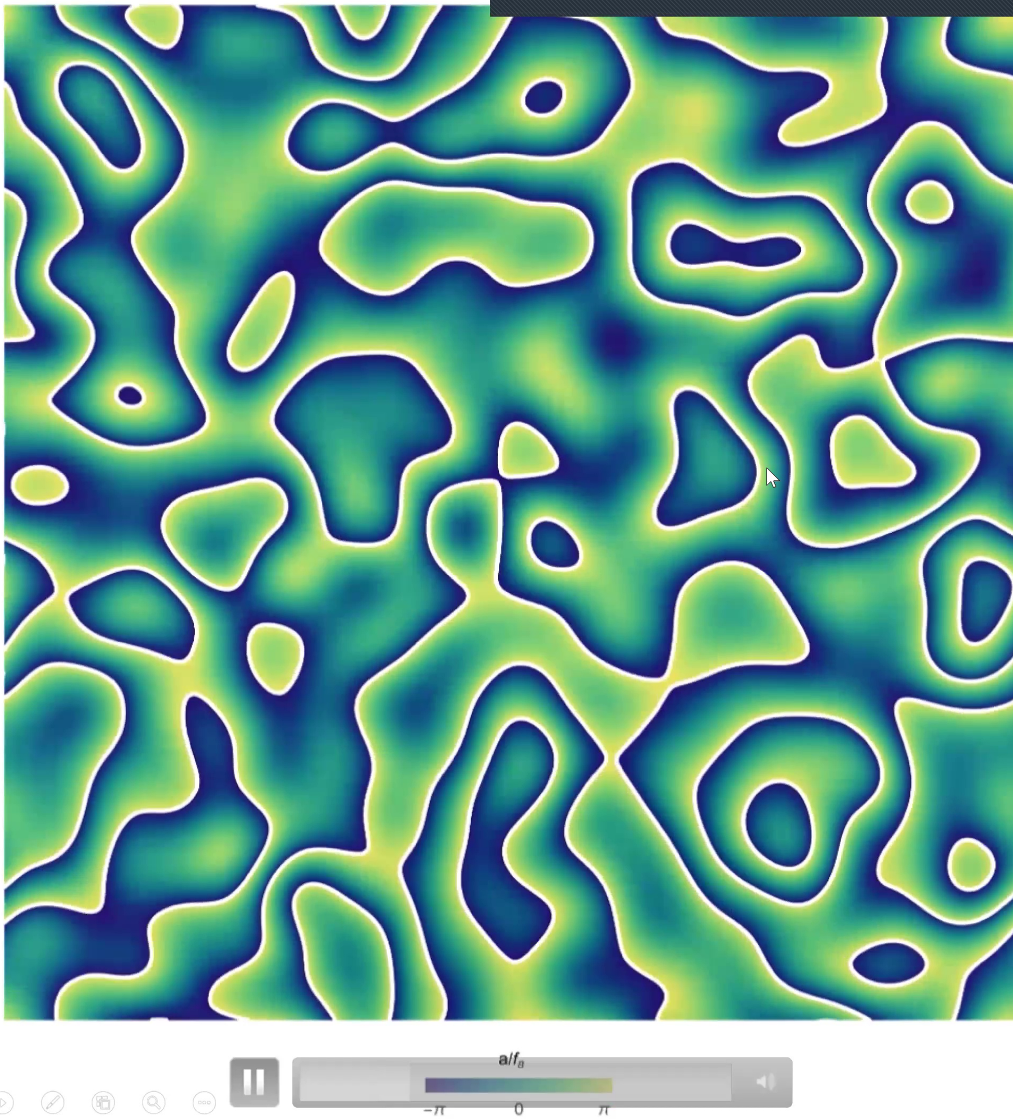
@ $H_\star$

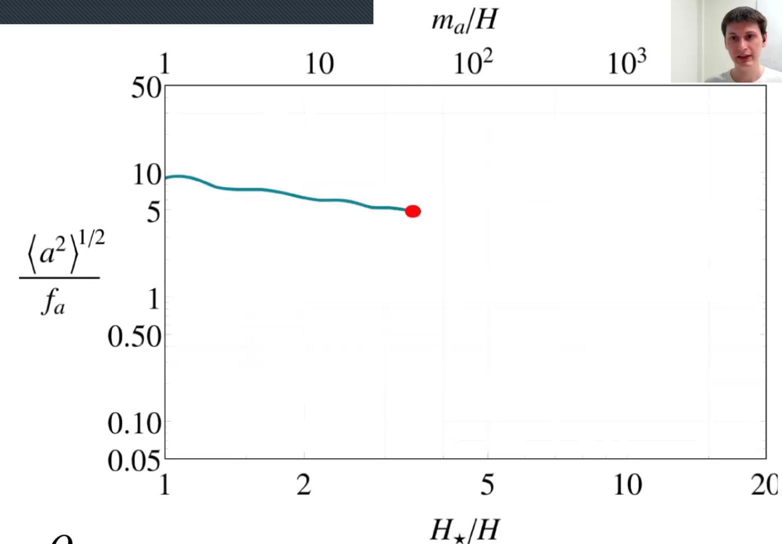
$$\rho_a \sim (\nabla a)^2 \sim H^2 a^2 \ \sim \xi \log H^2 f_a^2 \quad \Rightarrow \quad \frac{a}{2\pi f_a} \sim \sqrt{\xi \log} = O(10)$$

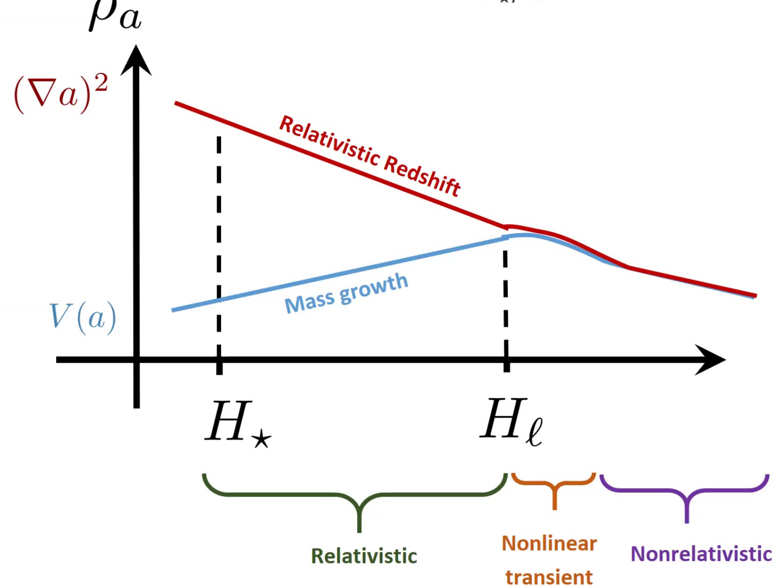




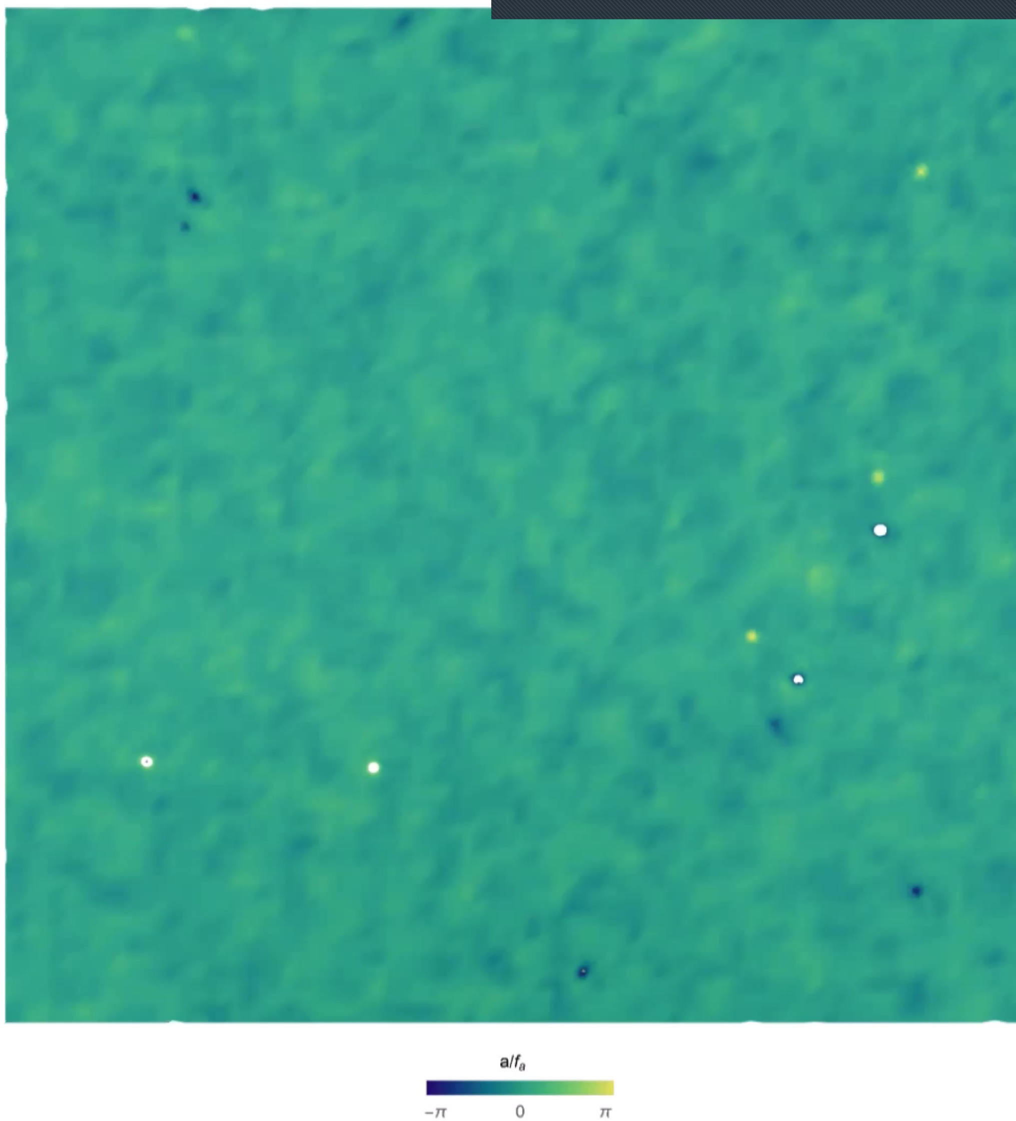
$$\ddot{a} + 3H\dot{a} - \frac{\nabla^2 a}{R^2} + m_a^2 f_a \sin\left(\frac{a}{f_a}\right) = 0$$


a/f_a
−π
0
π

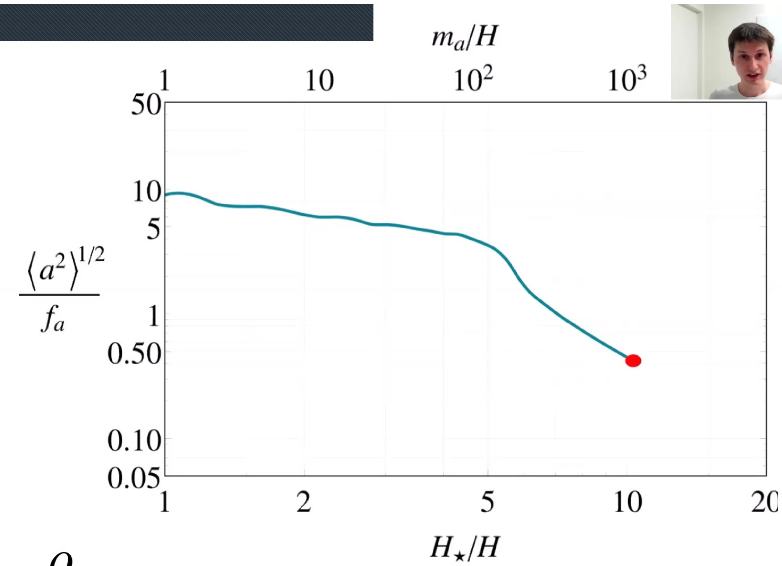

m_a/H
1
10
10^2
10^3
$\frac{\langle a^2 \rangle^{1/2}}{f_a}$
50
10
5
1
0.50
0.10
0.05
1
2
5
10
20
$H_\star/H$


ρ_a
$(\nabla a)^2$
Relativistic Redshift
$V(a)$
Mass growth
$H_\star$
H_ℓ
Relativistic
Nonlinear transient
Nonrelativistic

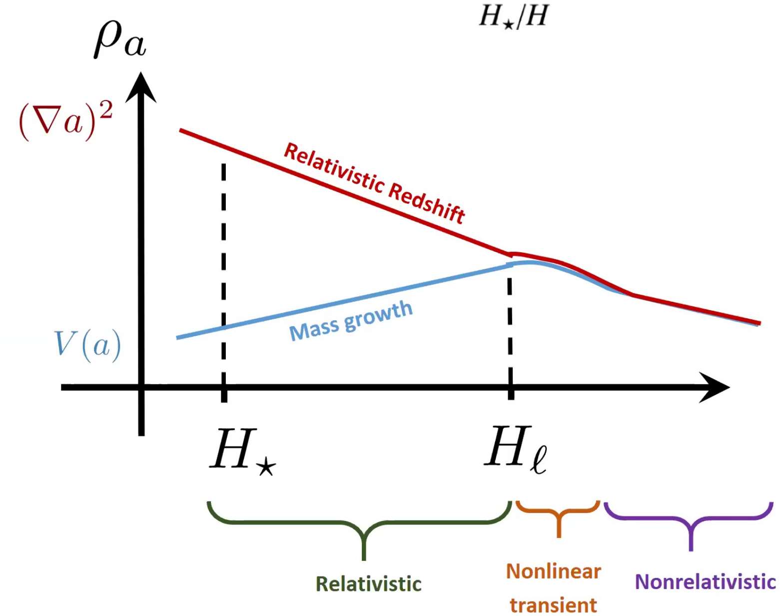
[redacted]



a/f_a
$-\pi$
0
π

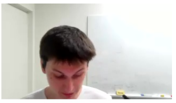


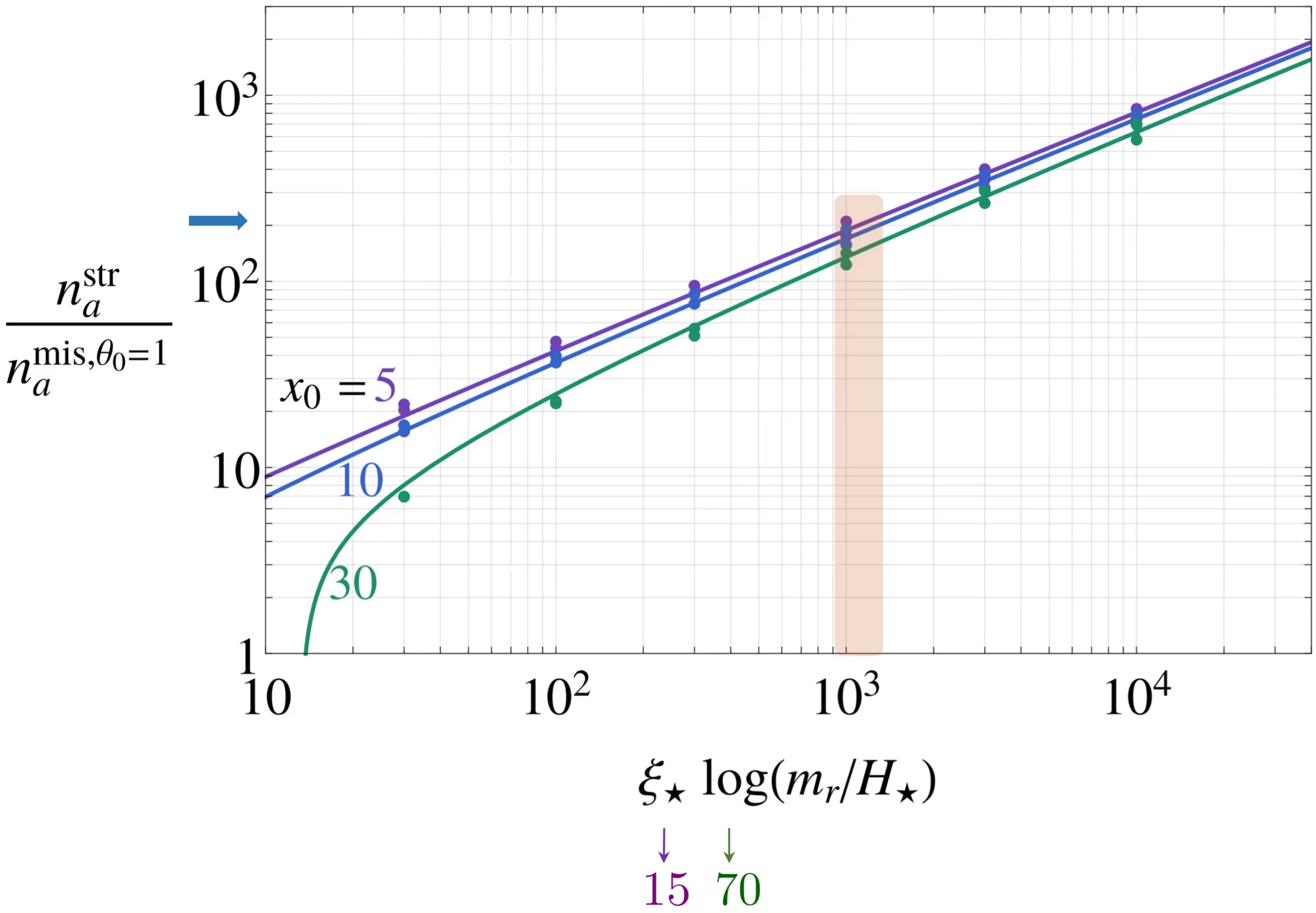
m_a/H
1
10
10^2
10^3
$\frac{\langle a^2 \rangle^{1/2}}{f_a}$
50
10
5
1
0.50
0.10
0.05
1
2
5
10
20
$H_\star/H$



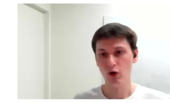
ρ_a
$(\nabla a)^2$
Relativistic Redshift
$V(a)$
Mass growth
$H_\star$
H_ℓ
Relativistic
Nonlinear transient
Nonrelativistic

The Number Density





3) Number density after the nonlinear regime

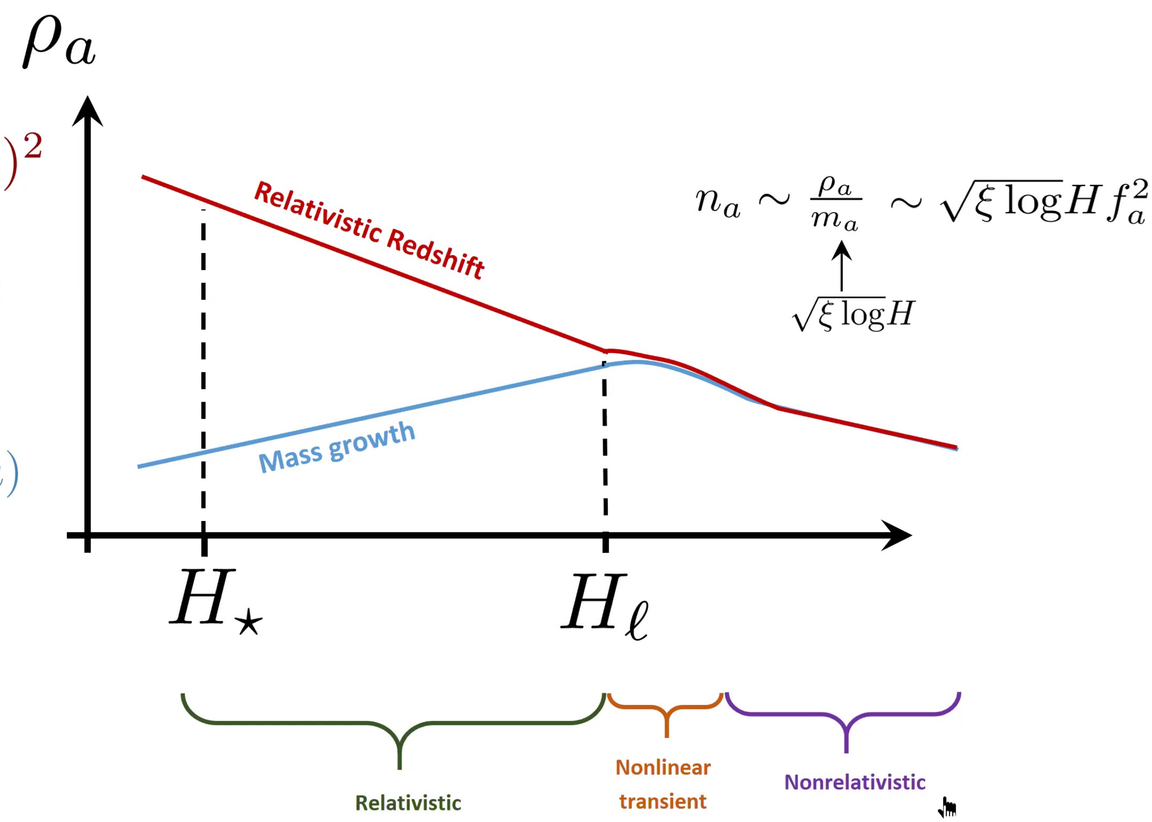


$@\ H = m_a \equiv H_\star$

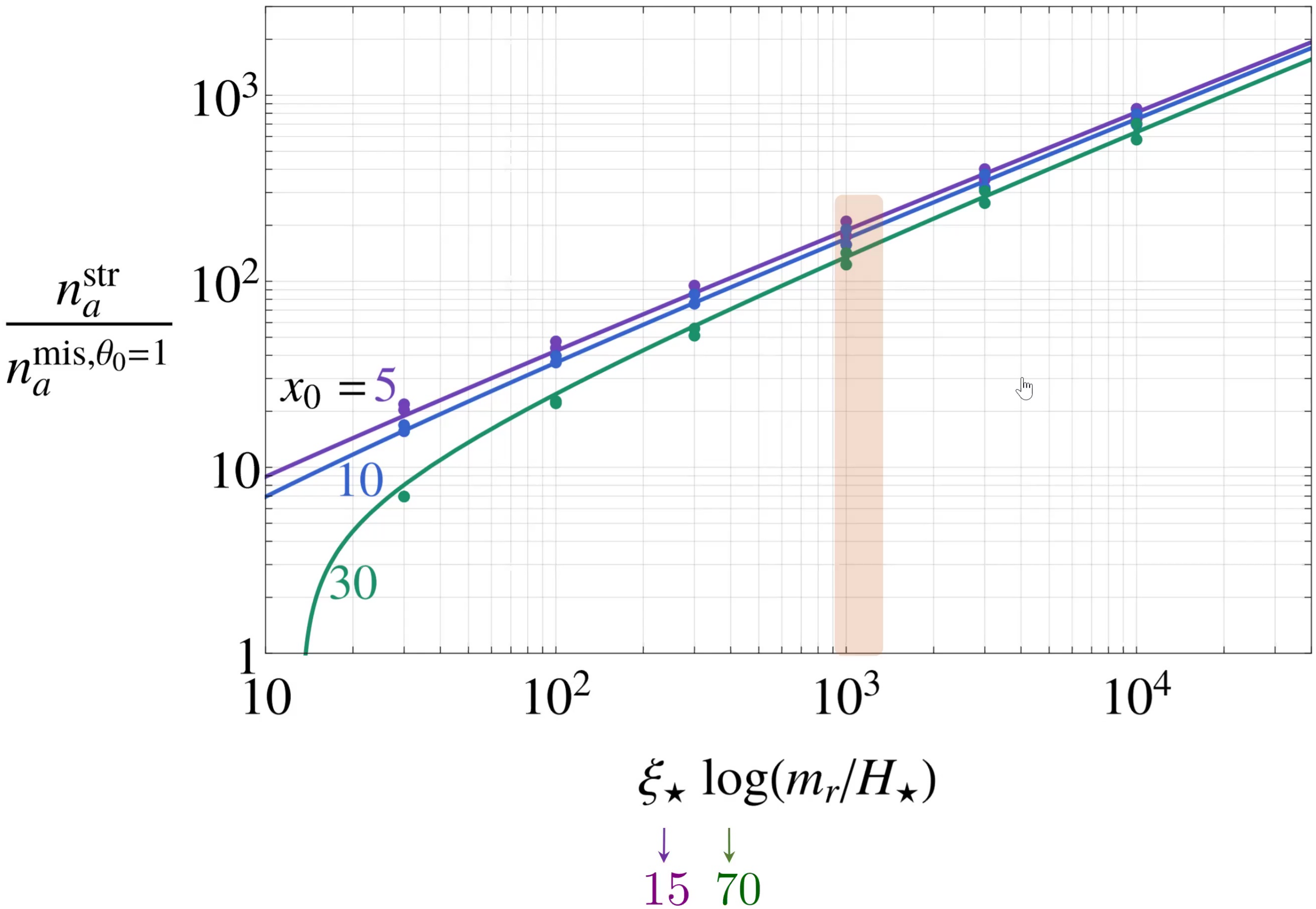
$$\frac{\xi\mu}{t^2} \sim 10^3 \left[\frac{\xi \log}{10^3}\right] H^2 f_a^2 \sim \quad (\nabla a)^2$$

$$@\ H_\star \quad \gg$$

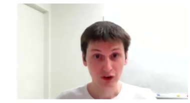
$$m_a^2 f_a^2 \sim \quad V(a)$$

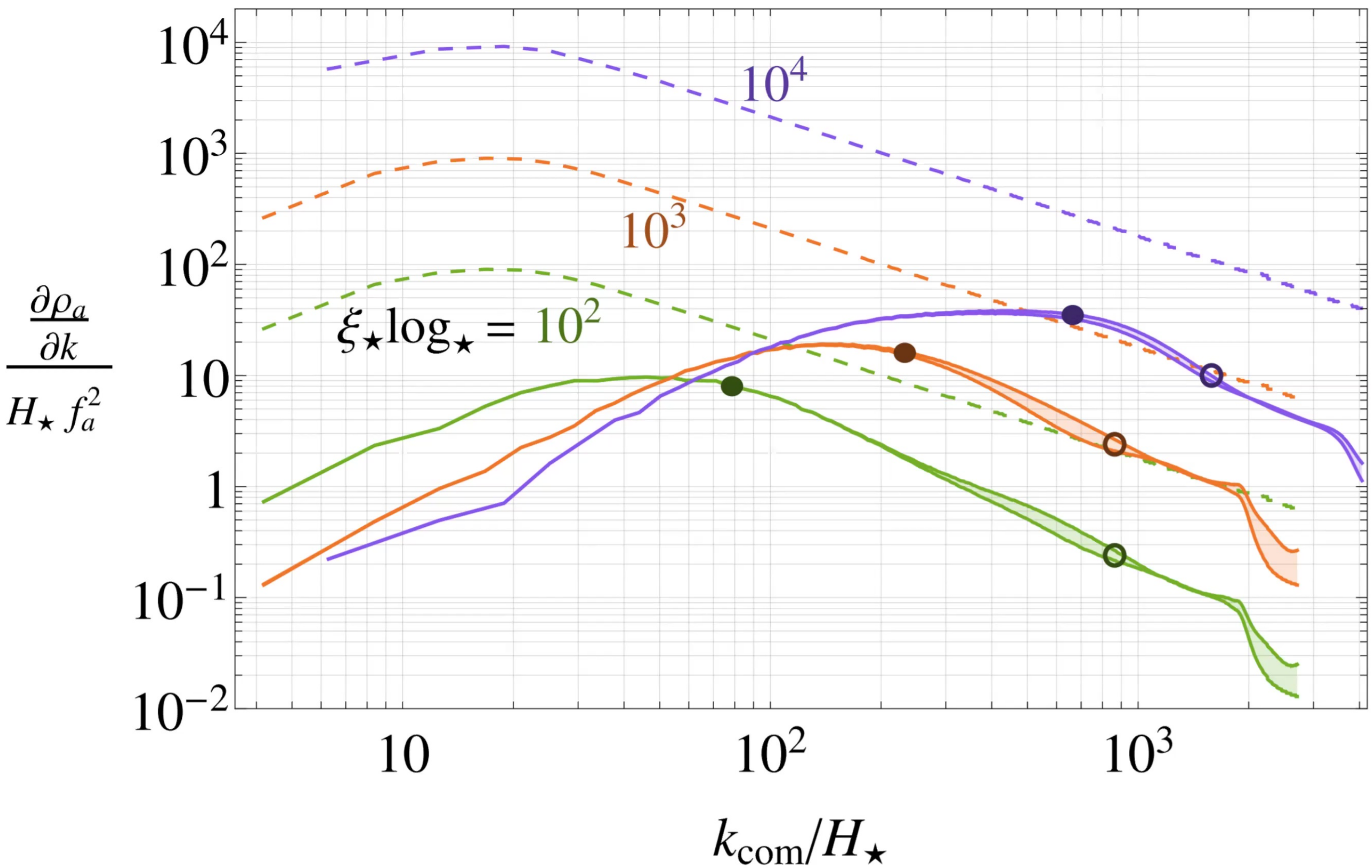


The Number Density



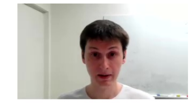
The Final Spectrum

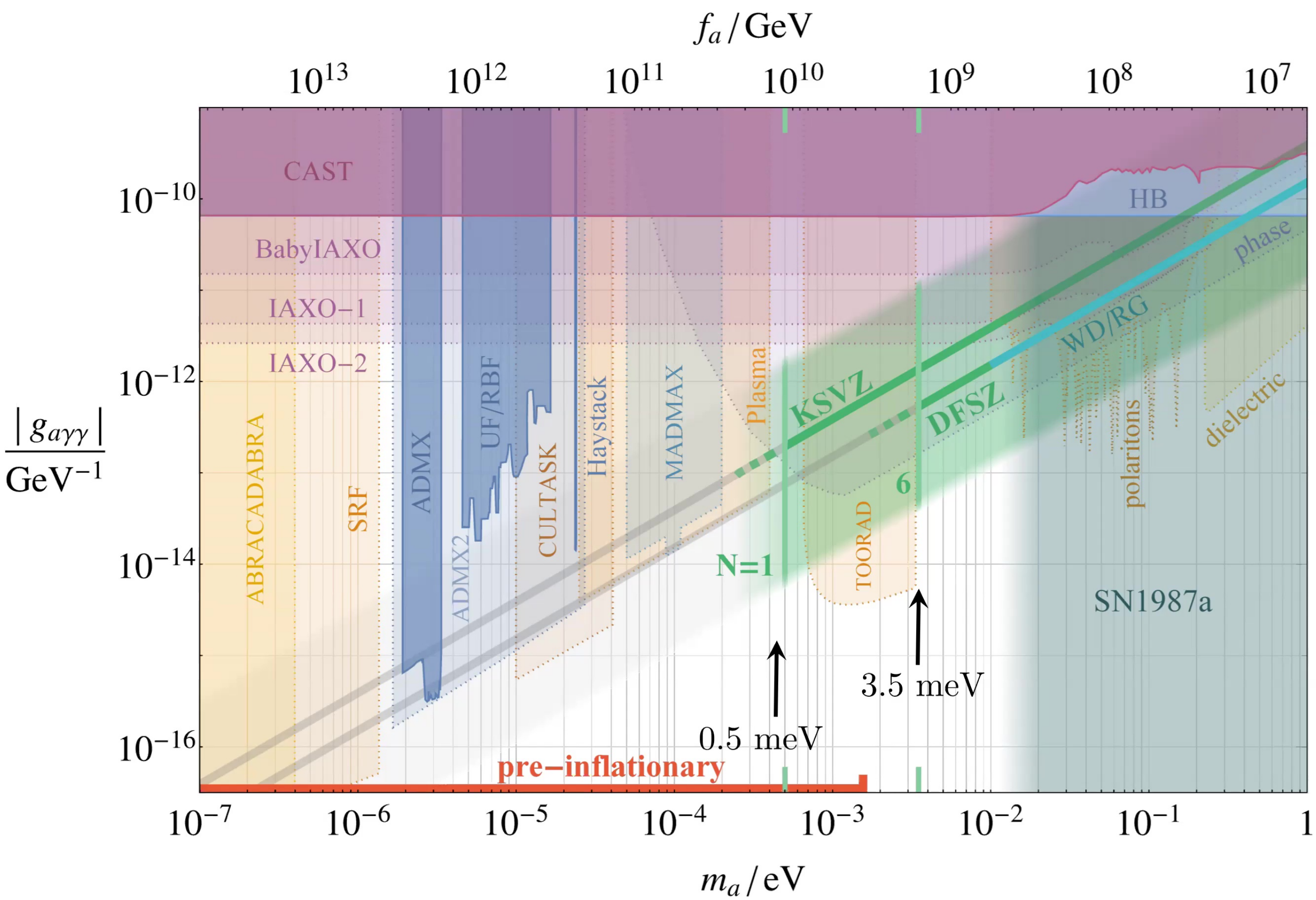




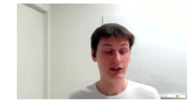
[redacted]

A Lower Bound on the Axion Mass





Conclusions



1) The system of axion strings is driven towards an attractor solution

- **evidence of logarithmic violations in ξ and q**
- **most conservative extrapolation implies More Axions from Strings**

2) The Axions from Strings experience nonlinear evolution at the QCD transition

- **a period of relativistic redshfit and a nonlinear transient:**

  A) partially reduce the number density

  B) make the spectrum more UV

$$\Longrightarrow \quad m_a \approx 0.5 \div 20 \text{ meV}$$