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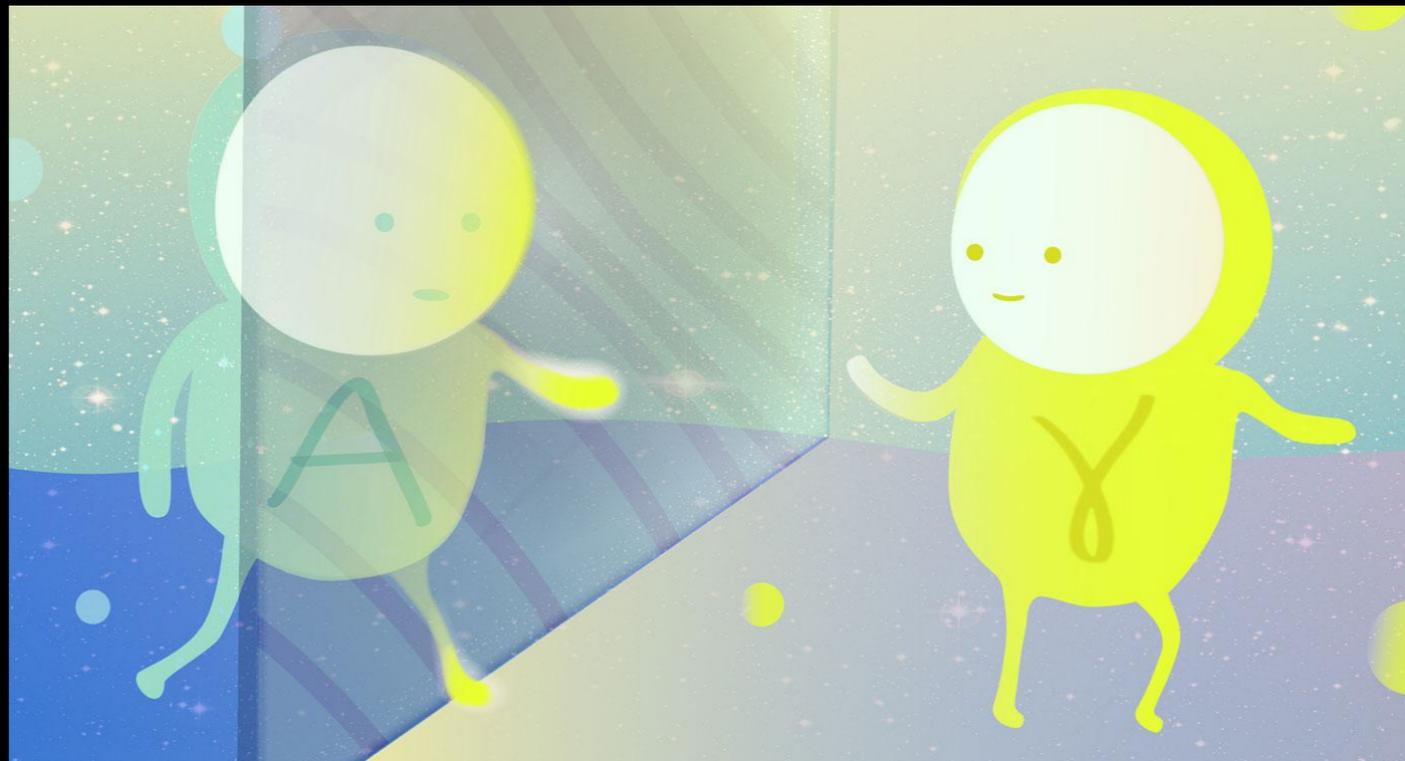
NORDITA

The Nordic Institute for Theoretical Physics



Stockholm
University

Probing the Early Universe with Axions

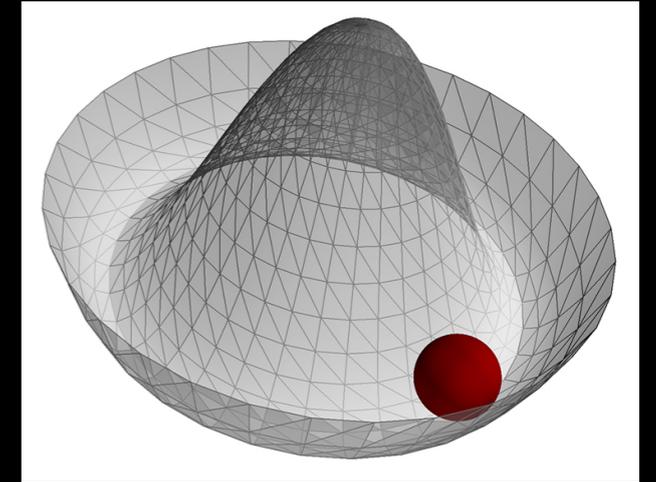


Luca Visinelli

Uppsala University & NORDITA

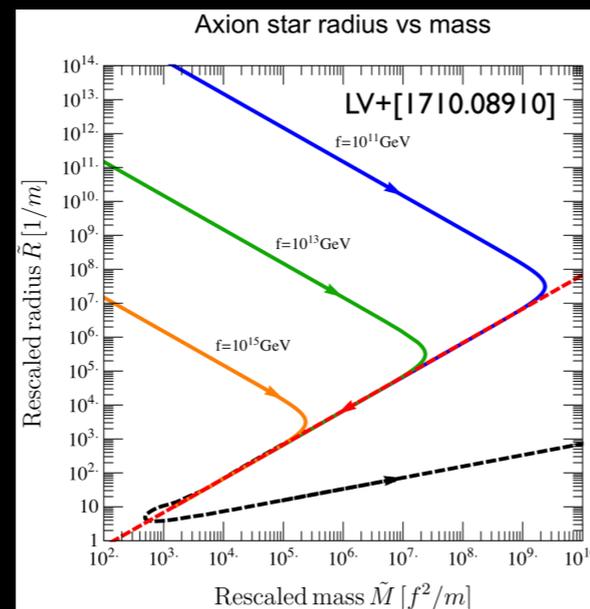
OUTLINE

1. The QCD axion and other axions

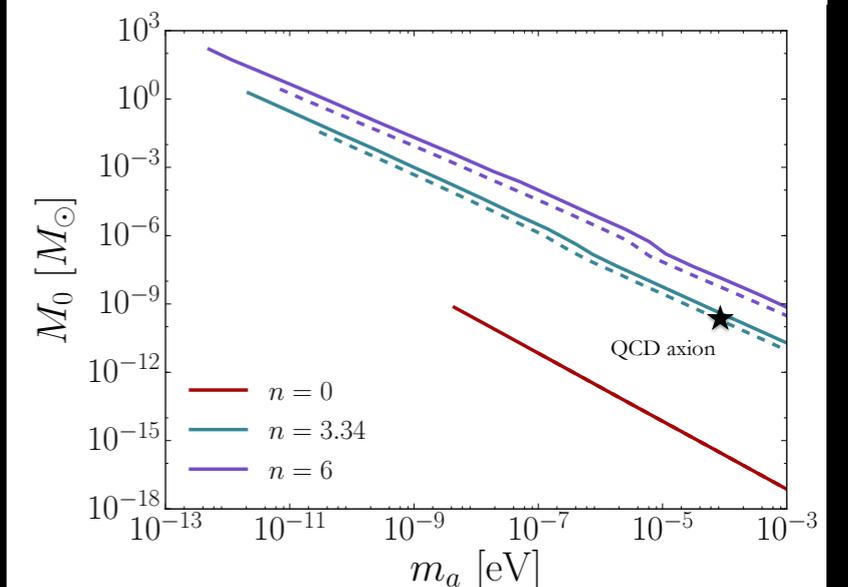


2. Axion miniclusters and prospects of detection

3. Axion stars

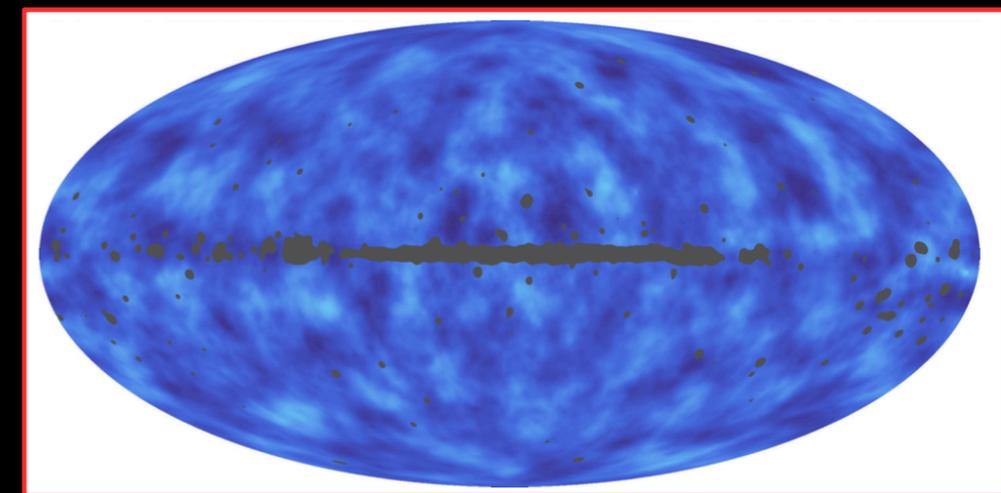
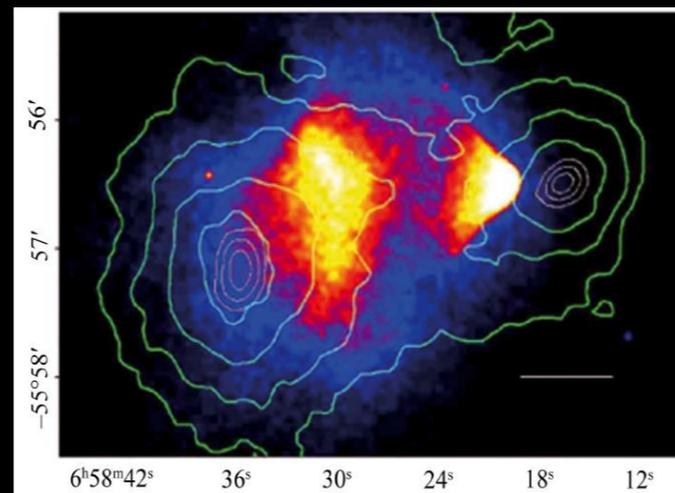
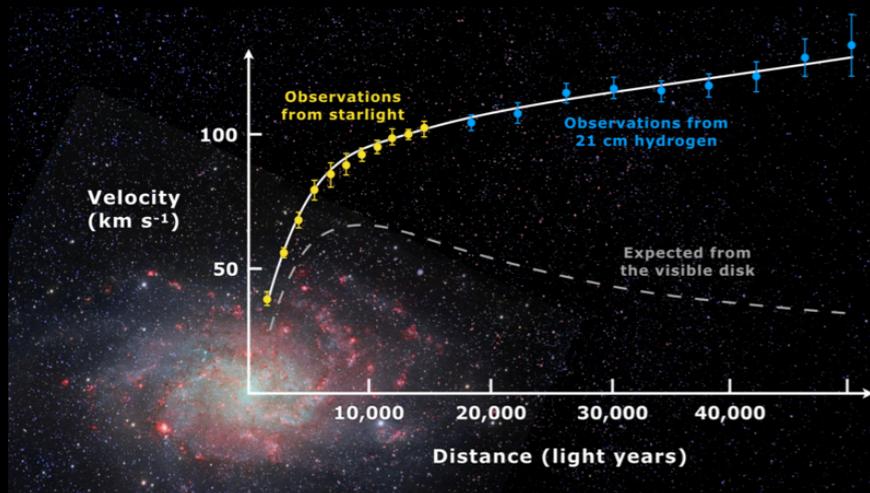


Mass of the minicluster



Overwhelming evidence for the existence of dark matter:

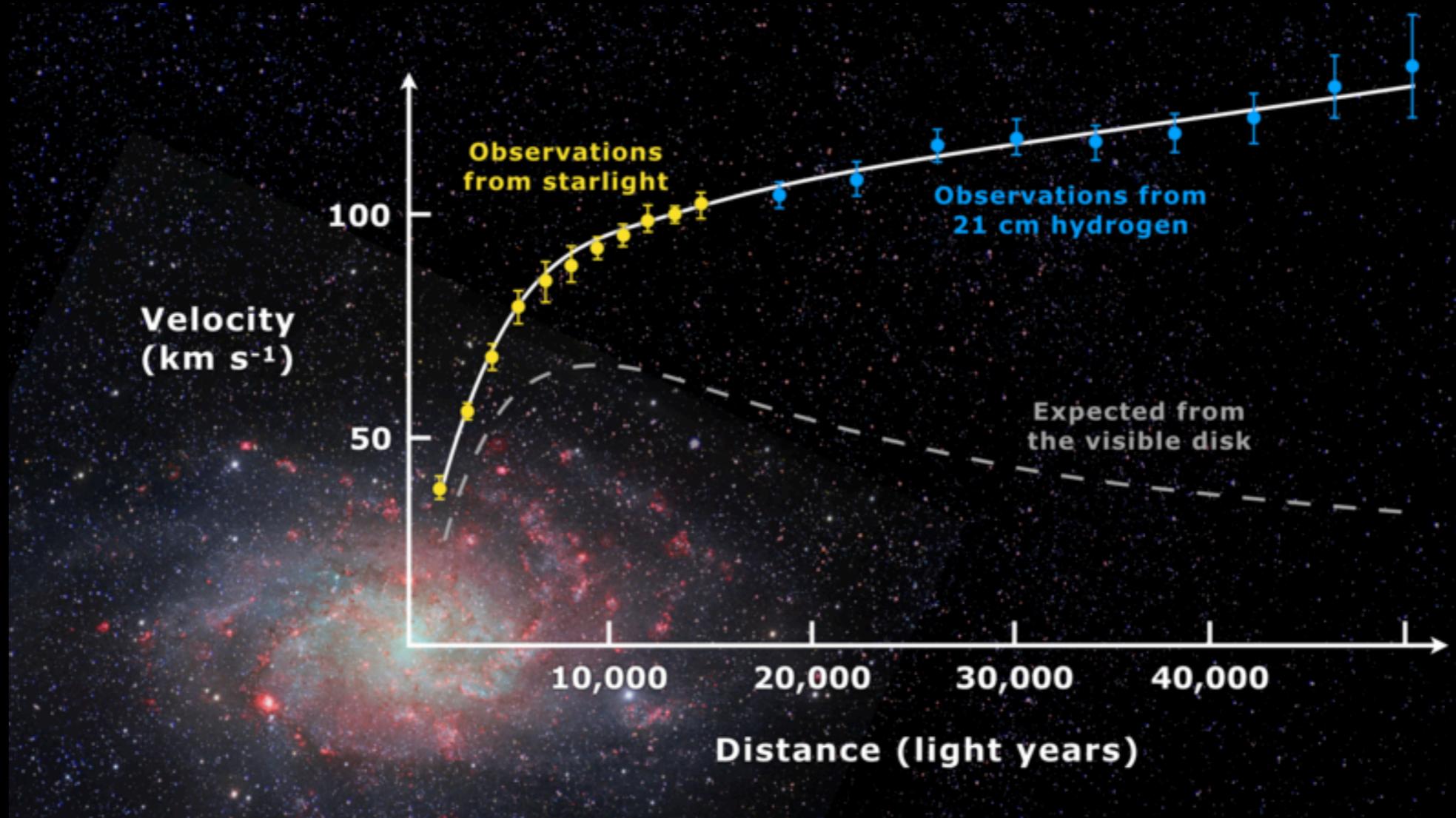
Rotational velocity curves of galaxies, Bullet Cluster, Gravitational lensing, acoustic peaks in the Cosmic Microwave Background (CMB) spectrum



The effects of dark matter span a wide range of scales

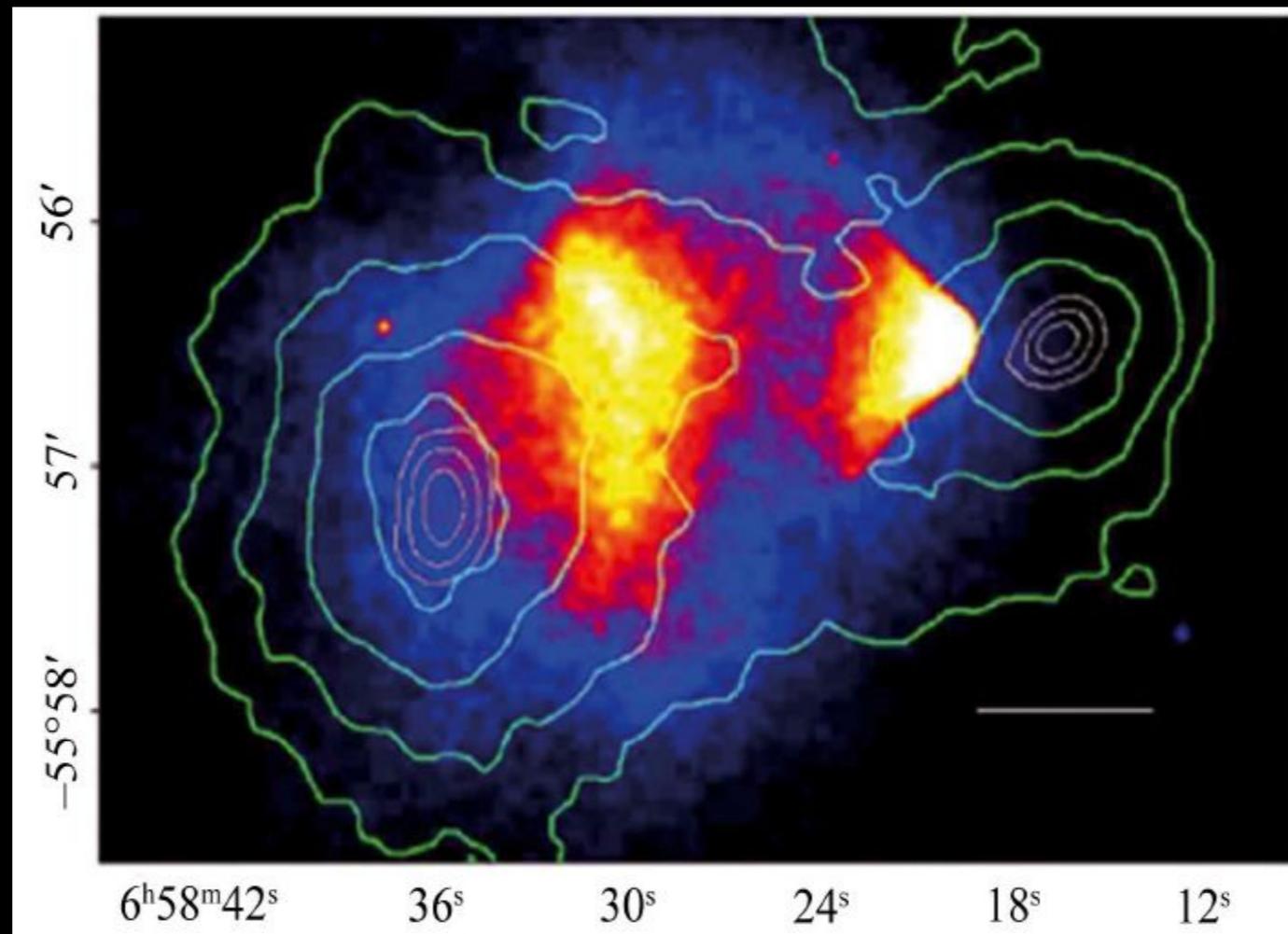
85% of the cold matter is “dark”, seeding structure formation

Rotational velocity curve of M33

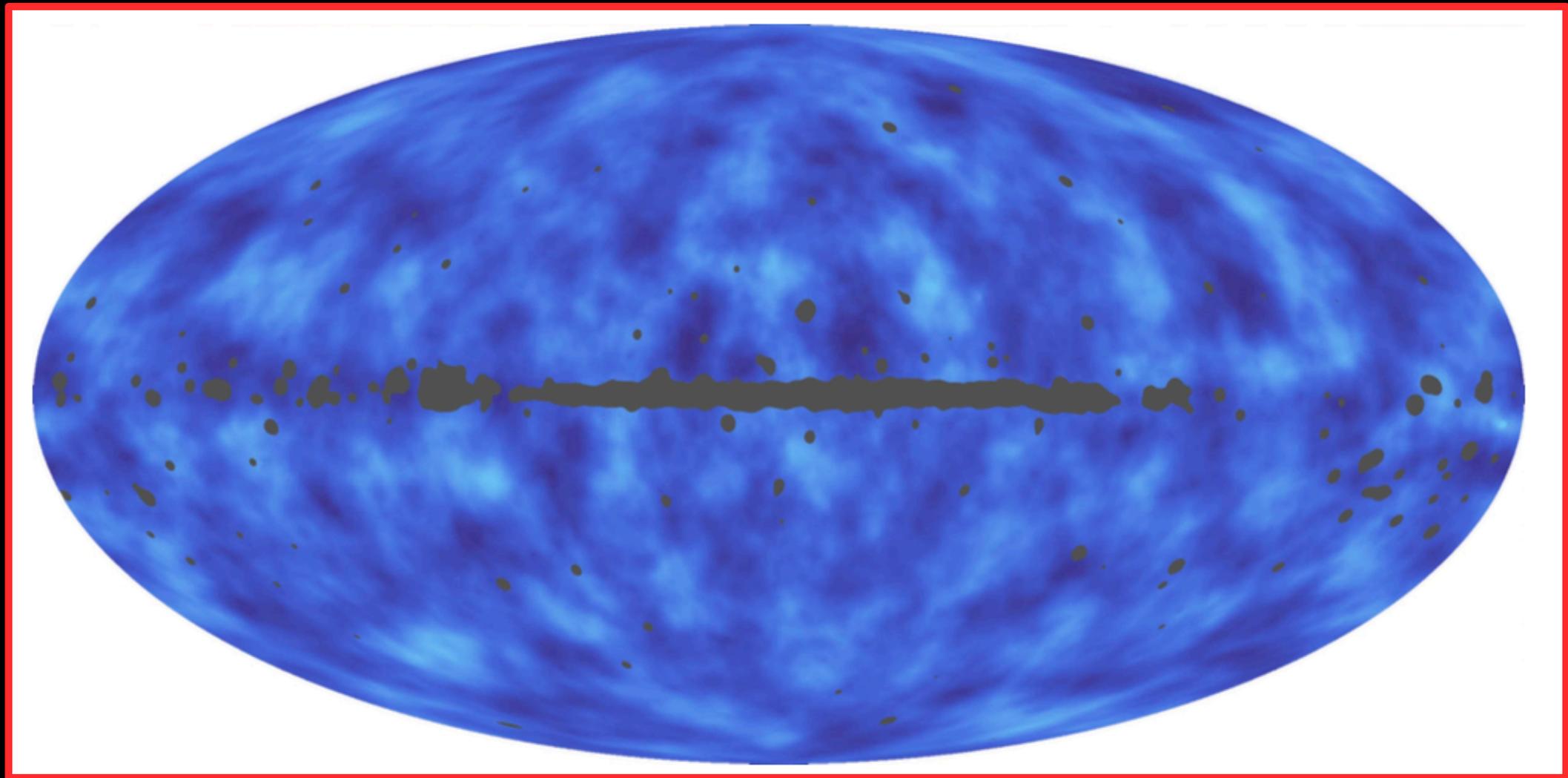


The Bullet Cluster

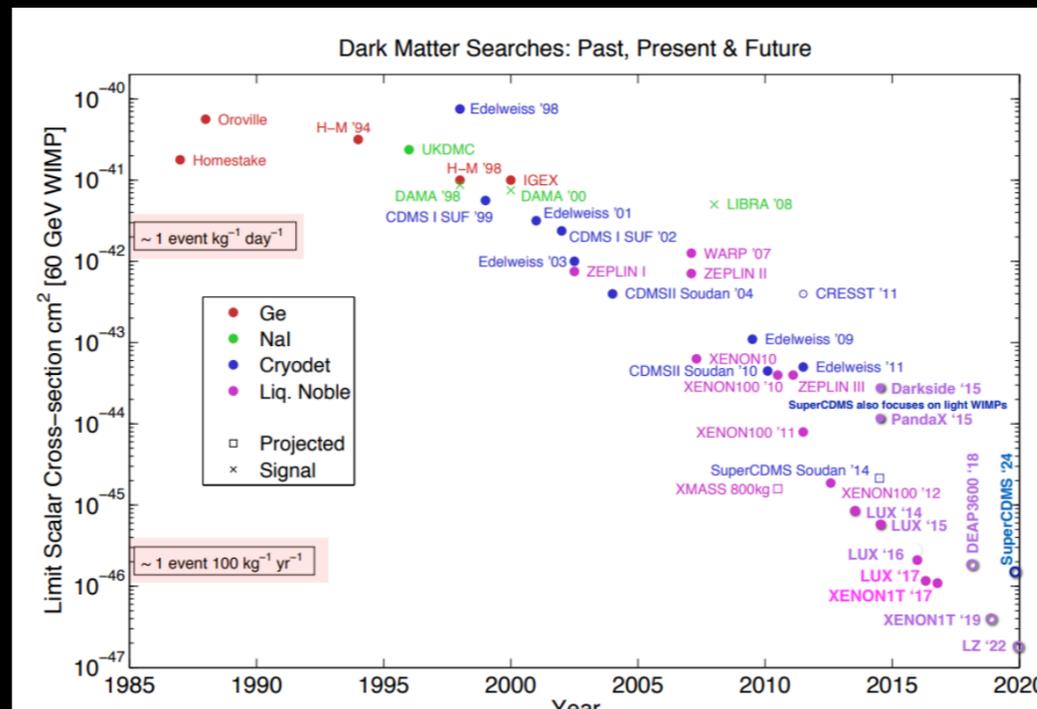
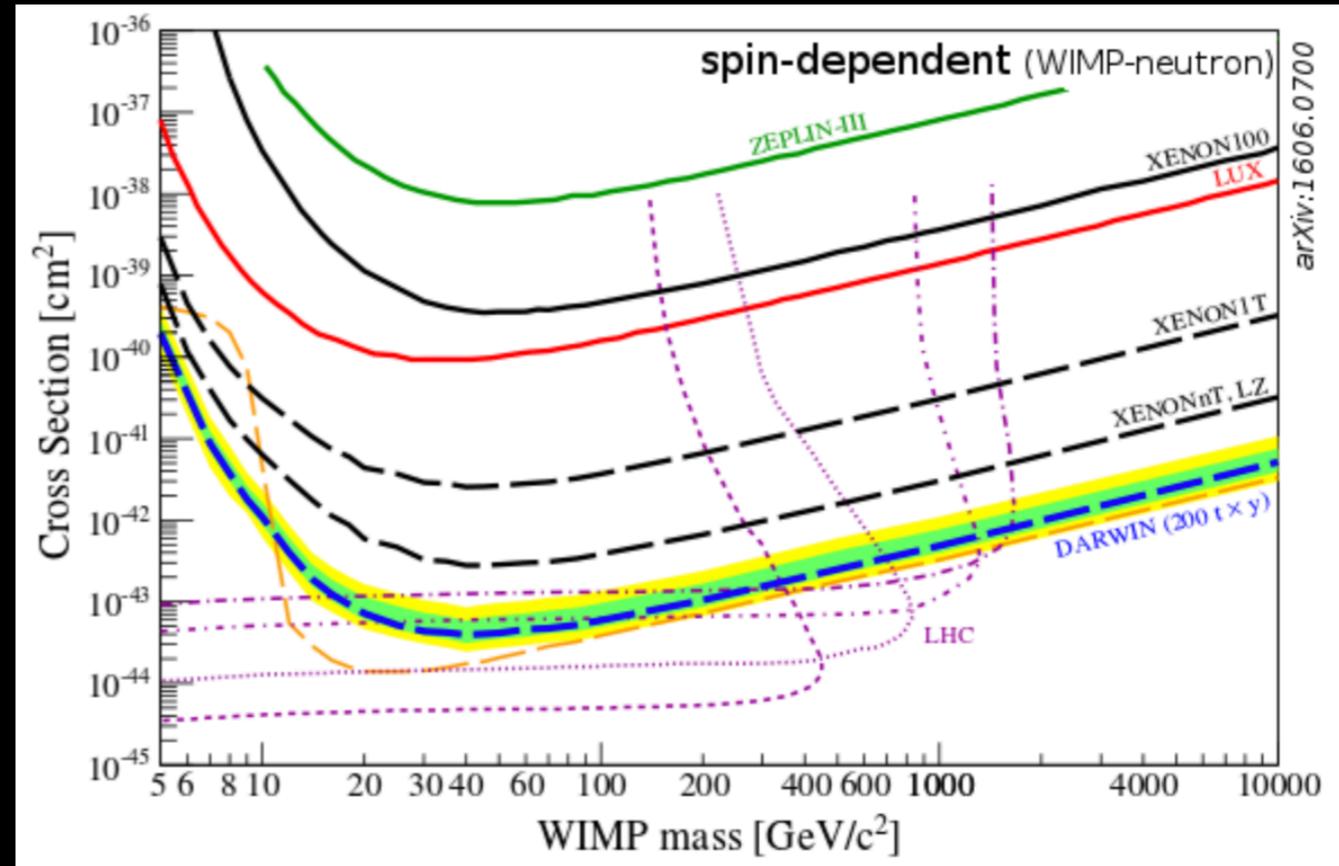
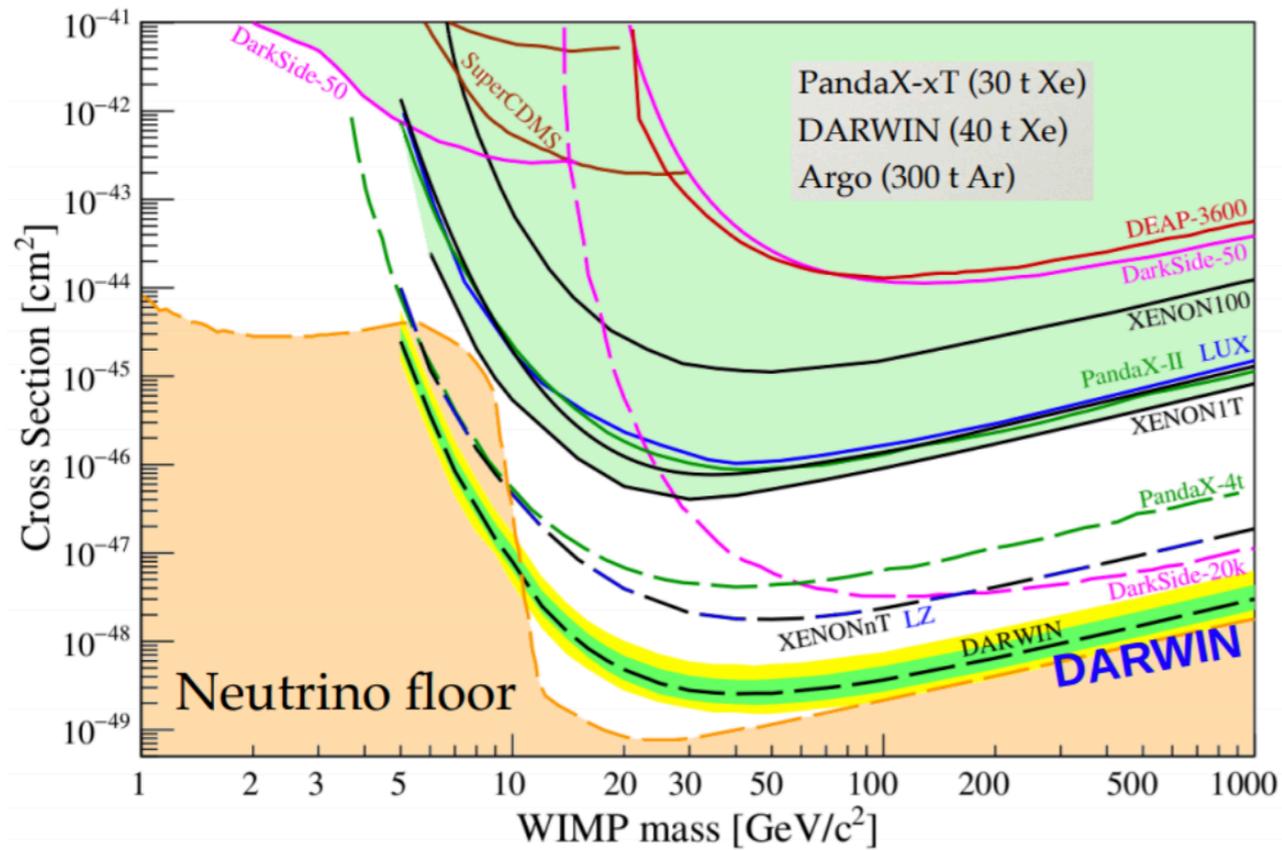
Upper bound on DM self-interactions $\sigma_\chi/m_\chi \lesssim 1 \text{ cm}^2/\text{g}$



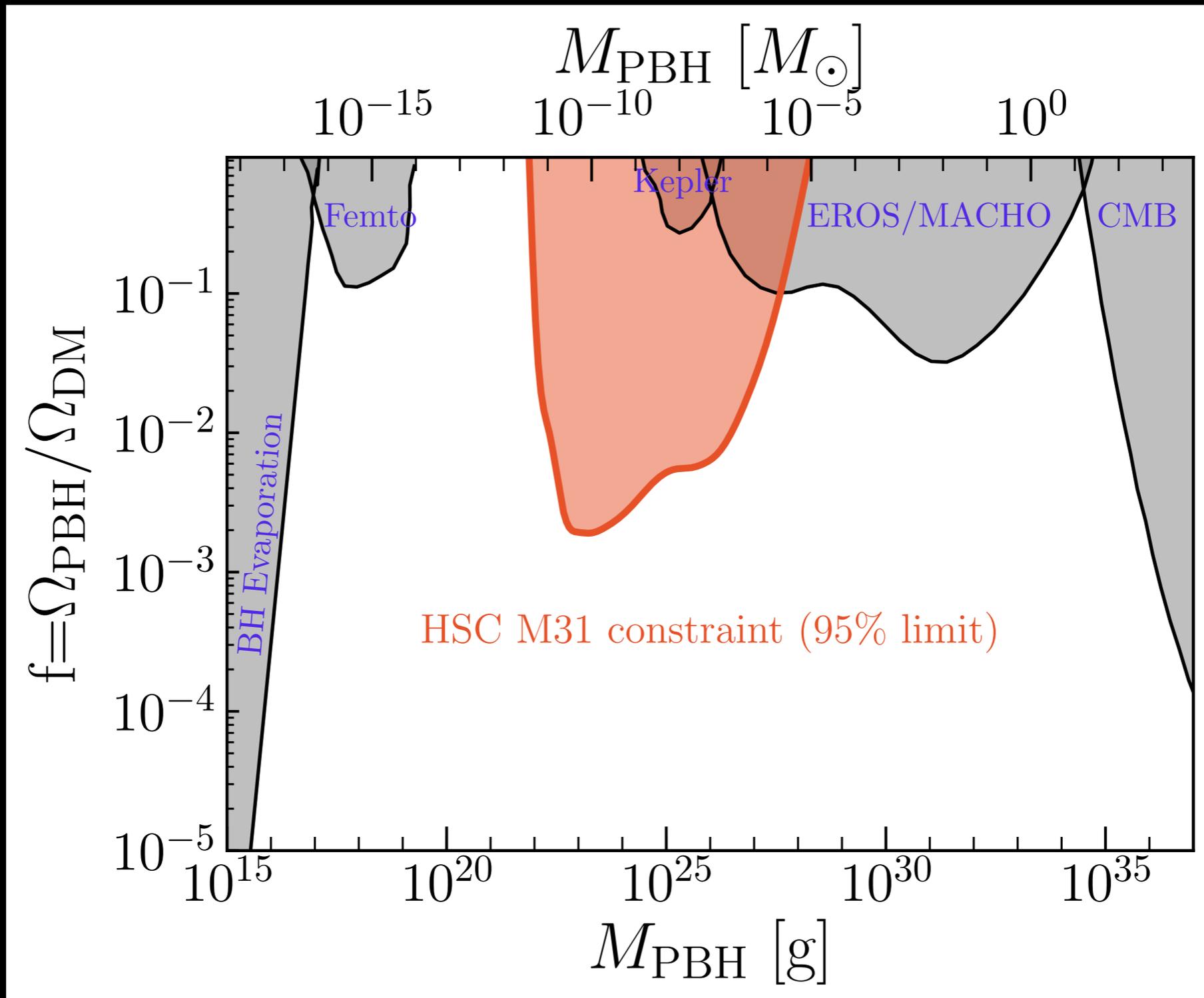
All-sky lensing map reconstructed from the PLANCK 2015 data



WIMP searches



Primordial Black Holes window?



Niikura+17; See also Nature Astron. 2019

Axions?

The value of $\bar{\theta}$ controls the matter-antimatter asymmetry in QCD

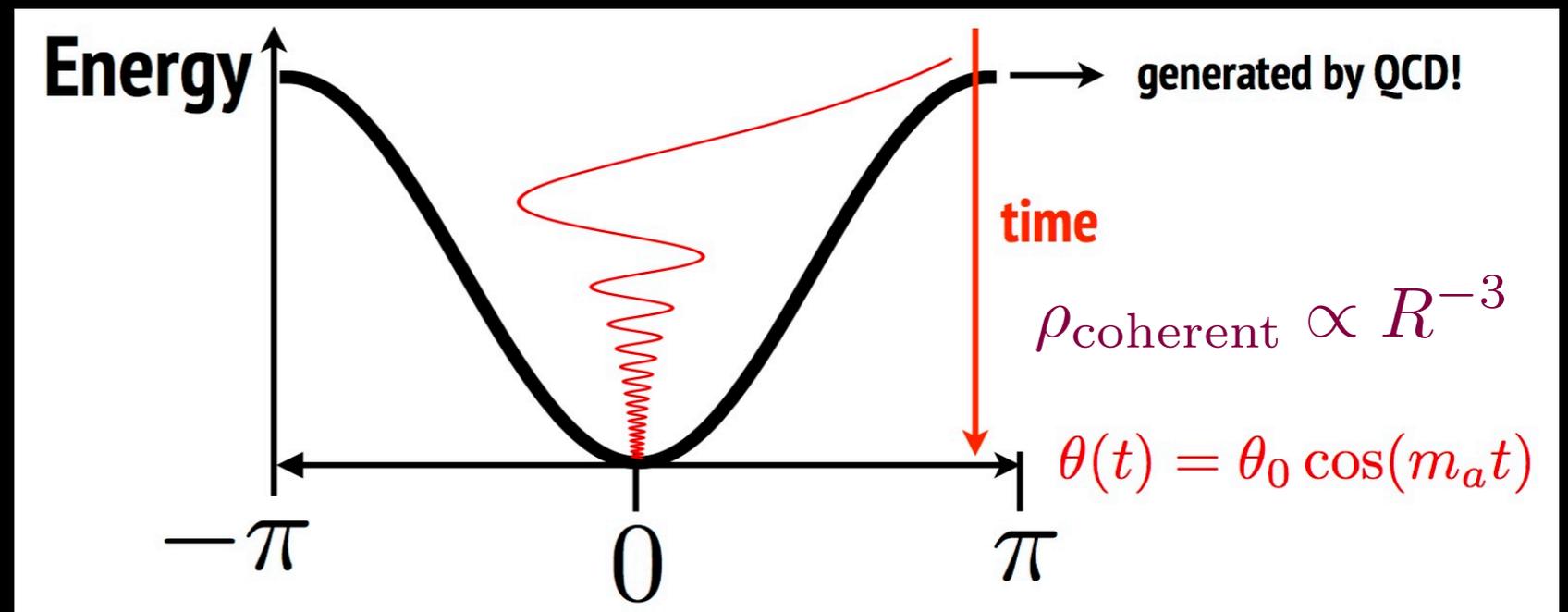
$$\mathcal{L}_{\text{strong,CP}} = \bar{\theta} \frac{\alpha_s}{2\pi} \text{Tr} (\mathbf{E}^\mu \mathbf{B}_\mu)$$

A similar term arises from EW, $\theta = \bar{\theta} + \theta_{\text{weak}} \sim \mathcal{O}(1)$

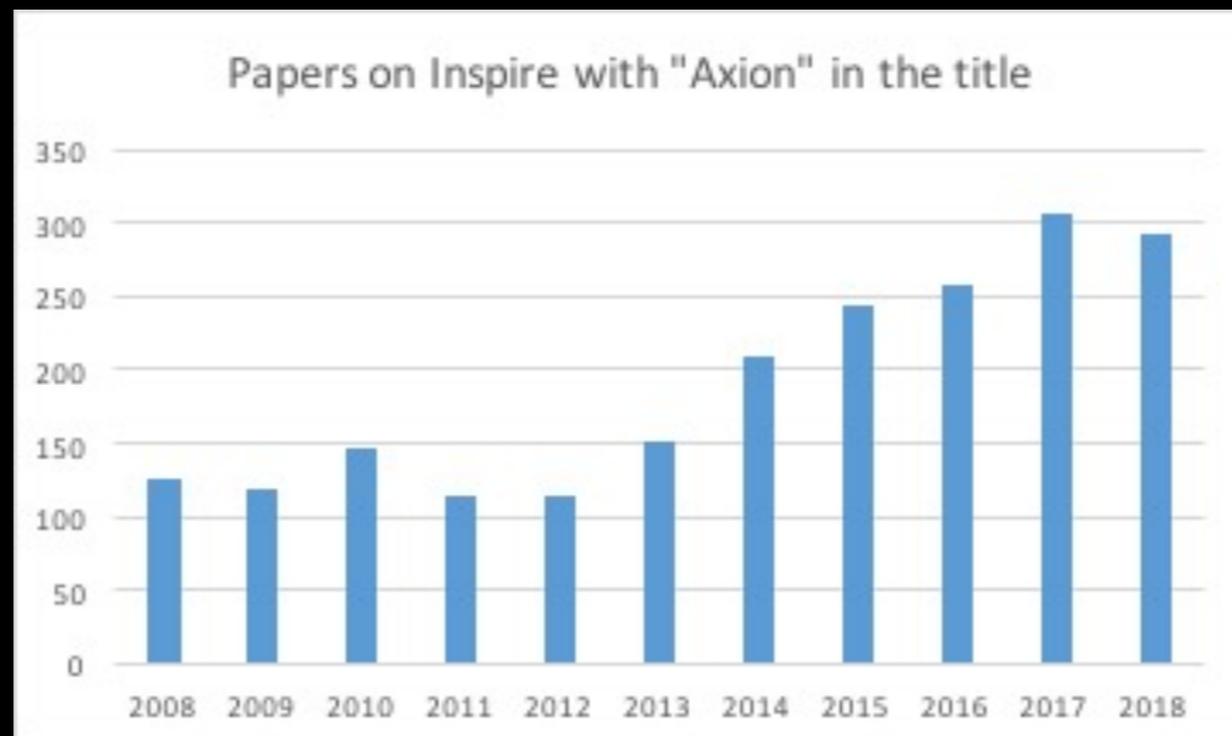
No observation of C and CP violation in Nature, $|\theta| \lesssim 10^{-10}$

Maybe it is a dynamical field?

$$\theta = \theta(t, \mathbf{x})$$



Steady growth in the interest on the axion



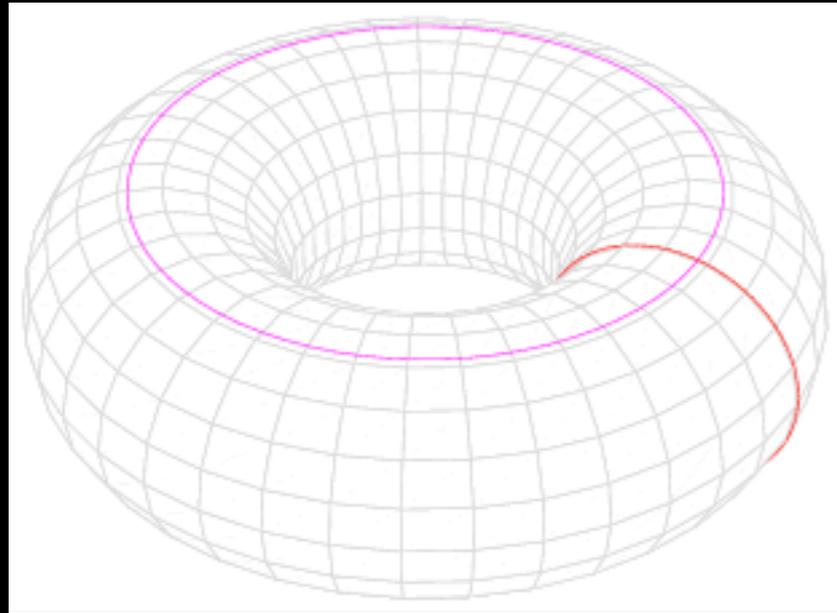
PATRAS @ DESY 2009



PATRAS @ DESY 2018



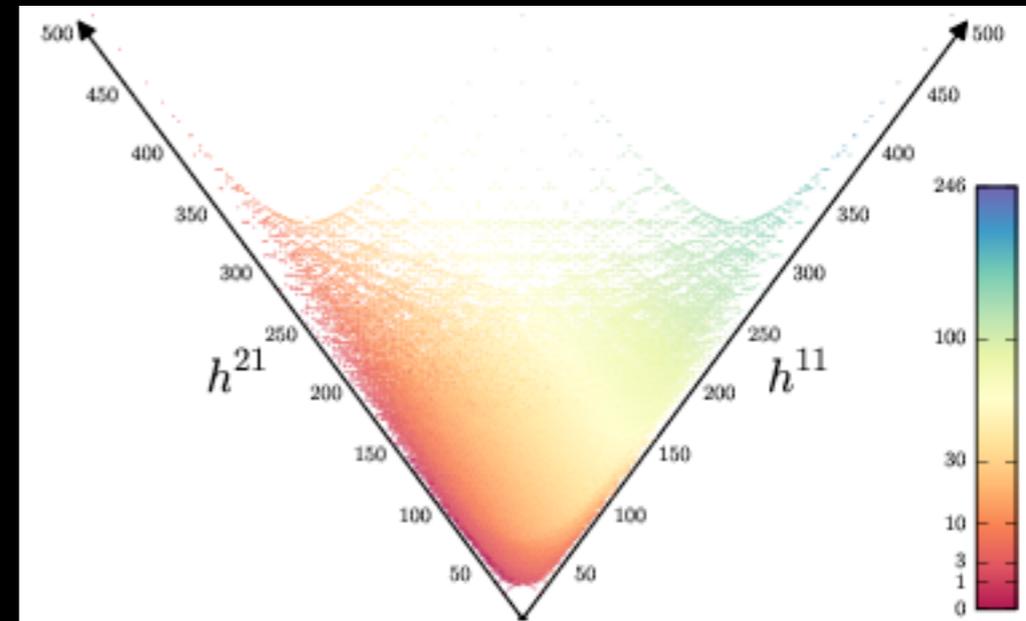
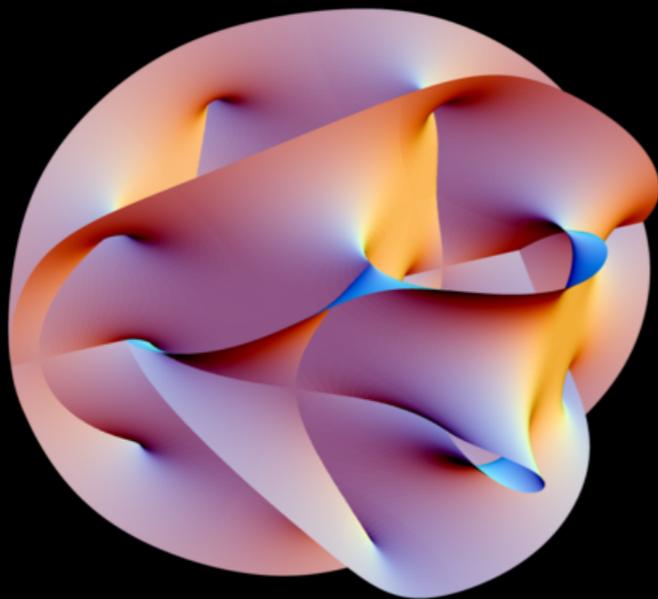
Axions from String Theory



A torus has two “moduli” fields
In general, # fields given by the
topology of the manifold

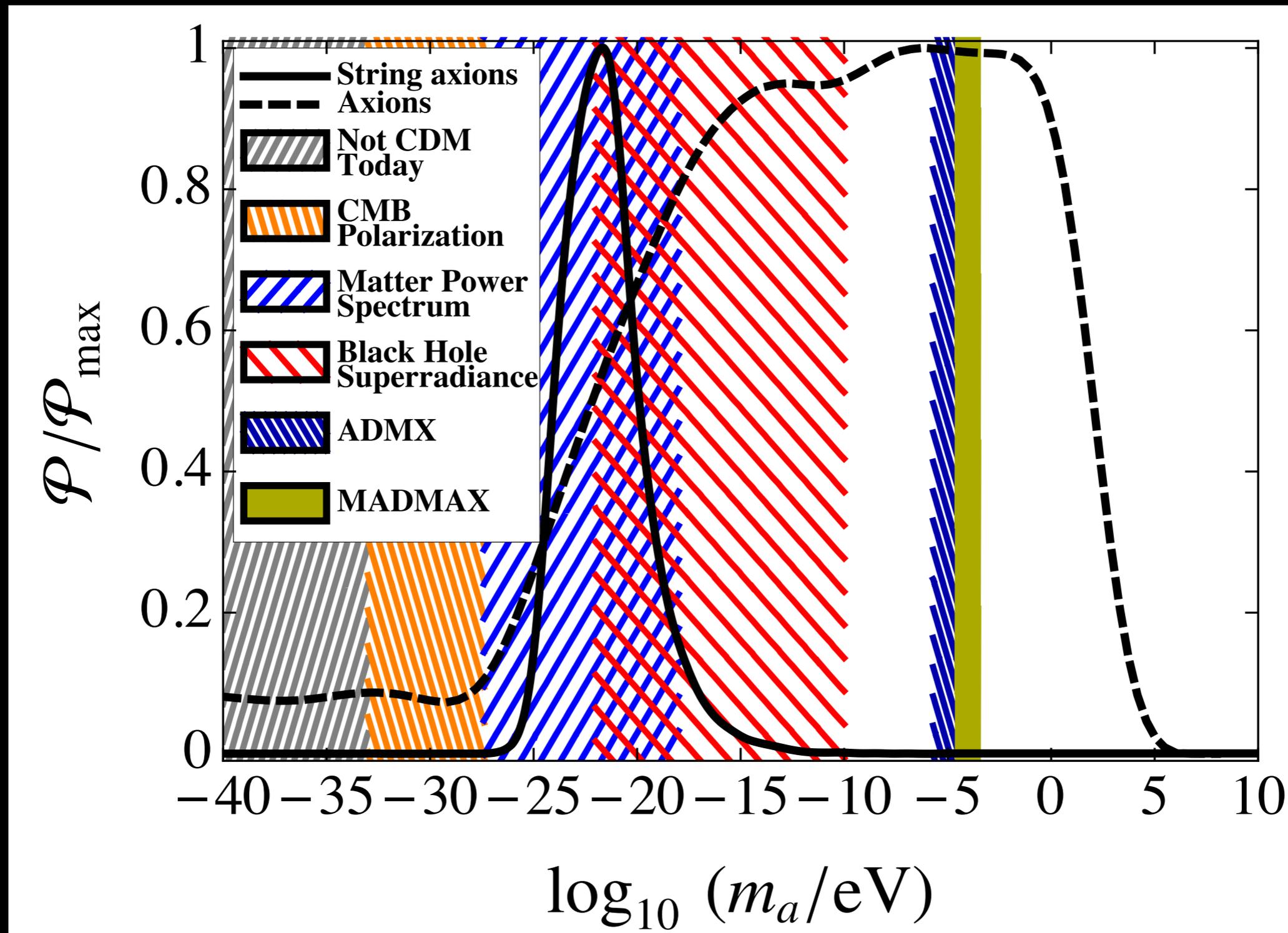
Moduli are paired with axions

A 6D manifold is more complicated than a torus...



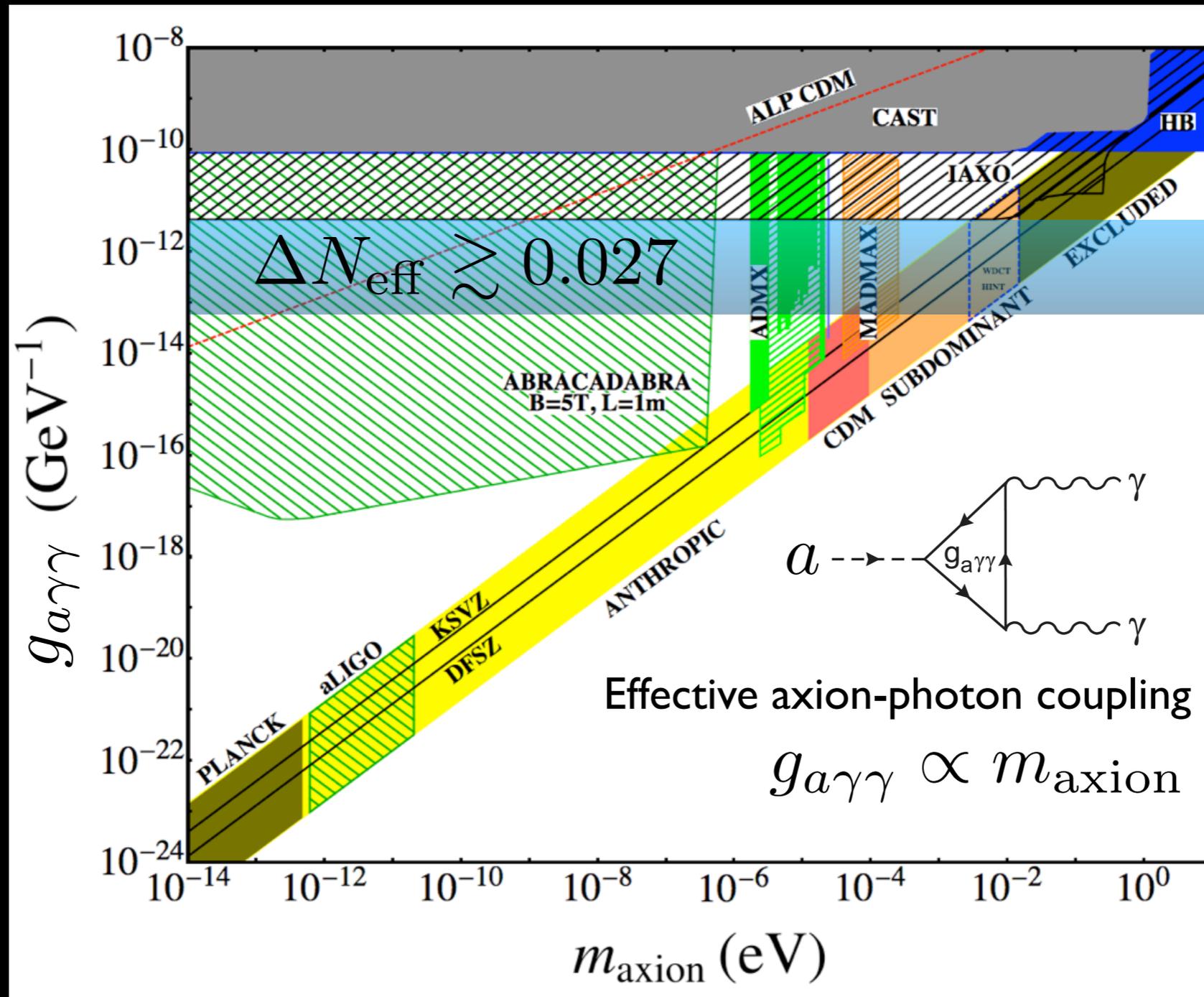
Density of Hodge numbers for all
known Calabi-Yau three-folds

Axions from String Theory



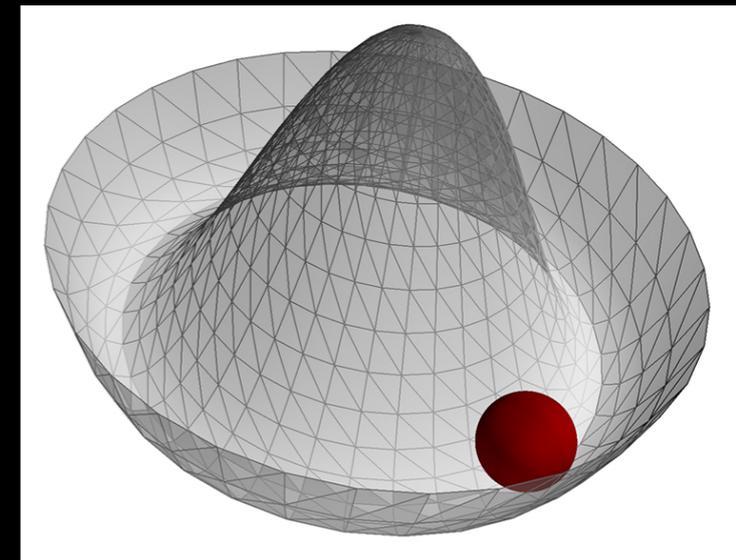
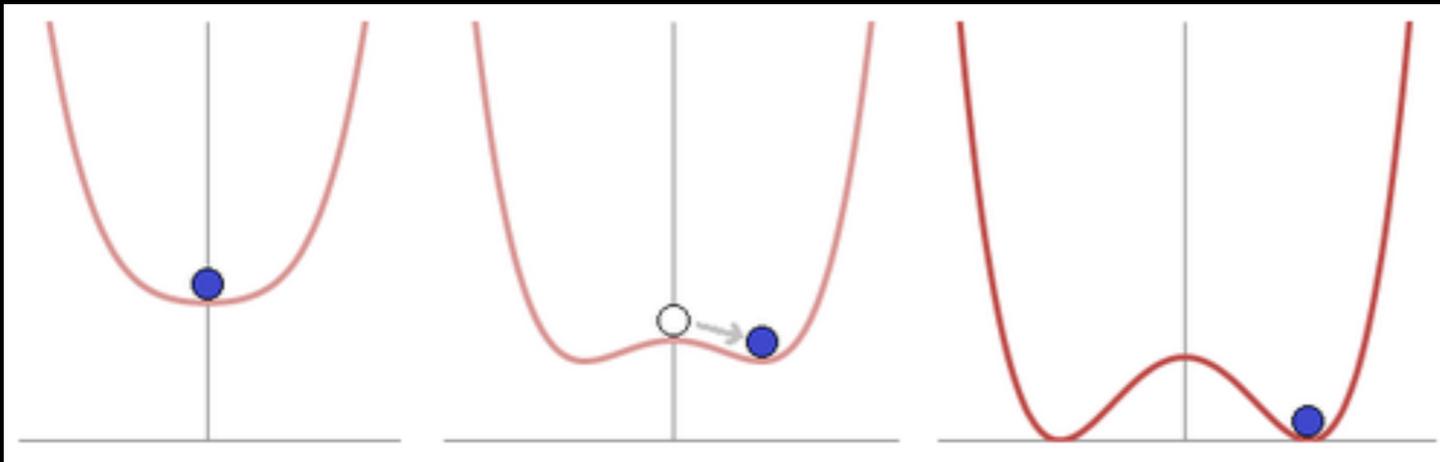
Visinelli and Vagnozzi, 1809.06382; see also GAMBIT results

One-parameter theory, falsifiable



Alternative DM candidate: the QCD Axion
 One-parameter theory, falsifiable

Early-Universe dynamics of the axion

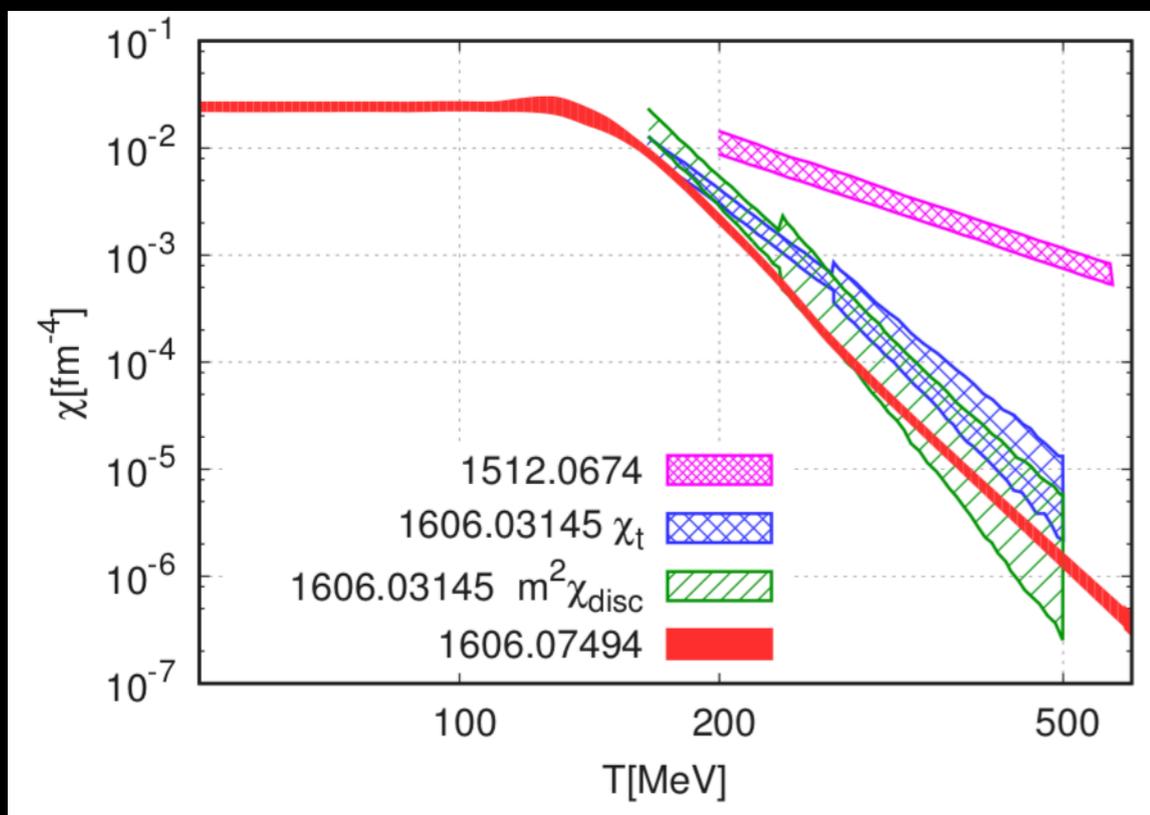


$$T \gtrsim f_a$$

$$T \sim f_a$$

$$T \lesssim f_a$$

$$T \sim \Lambda_{\text{QCD}} \ll f_a$$



Details on the temperature dependence still debated (semi-analytical, lattice simulations)

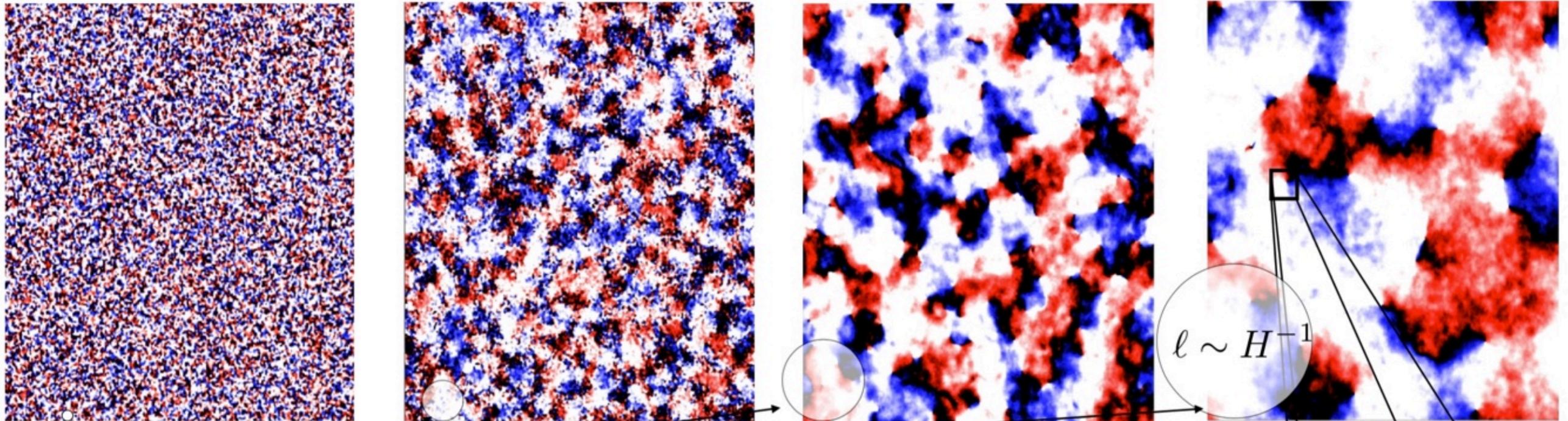
Destruction of the string-wall network

$$T \sim f_a$$

The Kibble mechanism (Kibble76)
leads to string network formation

$$T \sim T_{\text{QCD}}$$

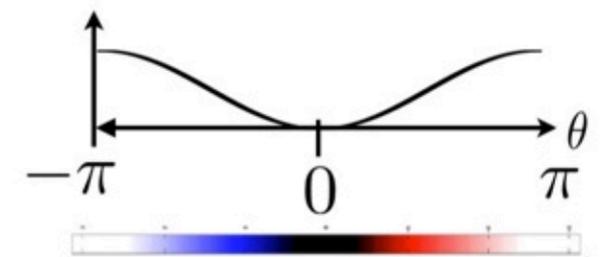
Domain walls form and dissipate
(Sikivie82; Georgi+82)



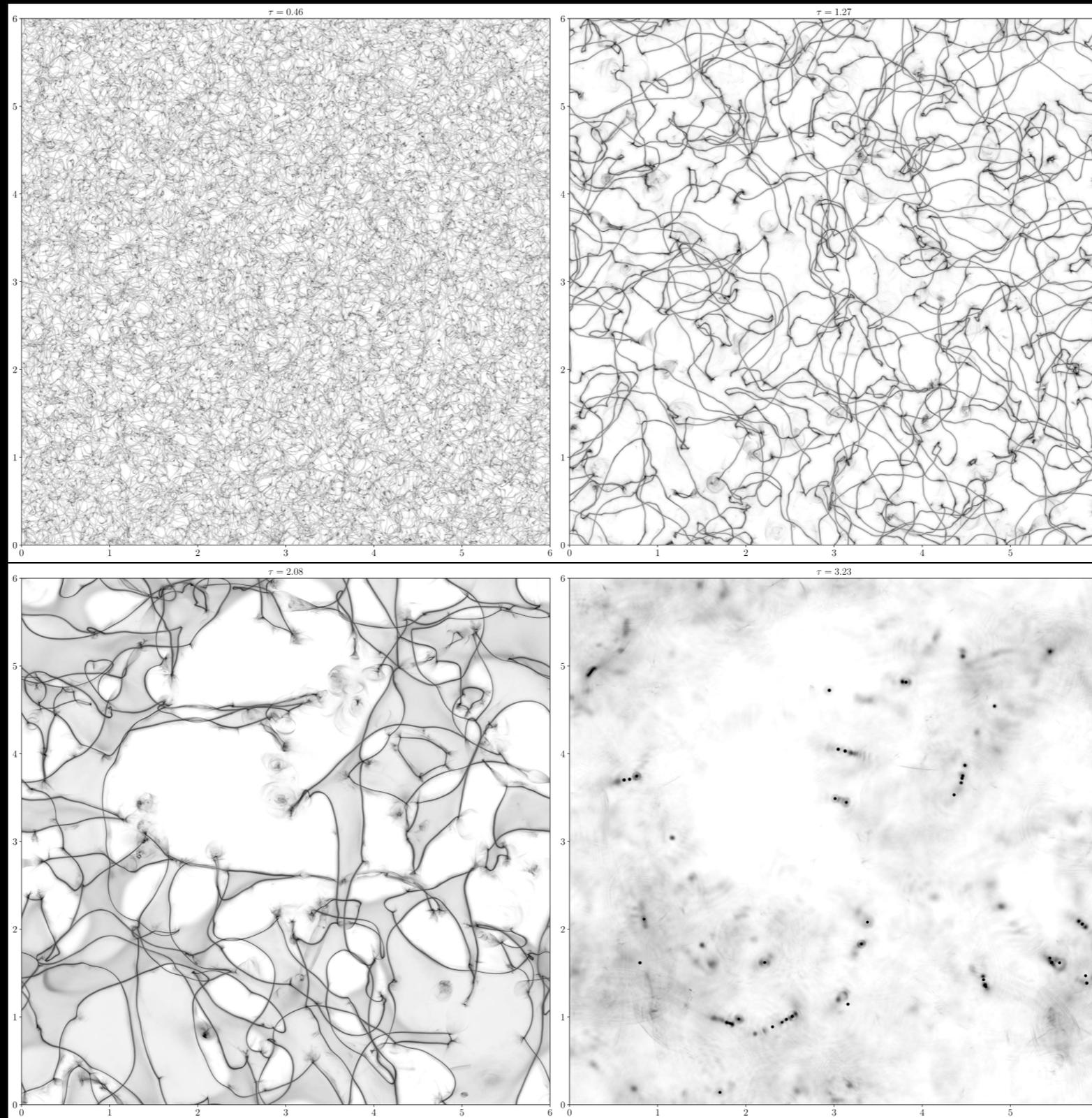
1 - Horizon size \sim time, fields become uniform \sim horizon size (Fourier modes start decaying when $t \sim 1/k$)

Computationally challenging:
all scales from the size of the box H_{QCD}^{-1}
to the string core f_a^{-1} have to be resolved!

Courtesy of J. Redondo

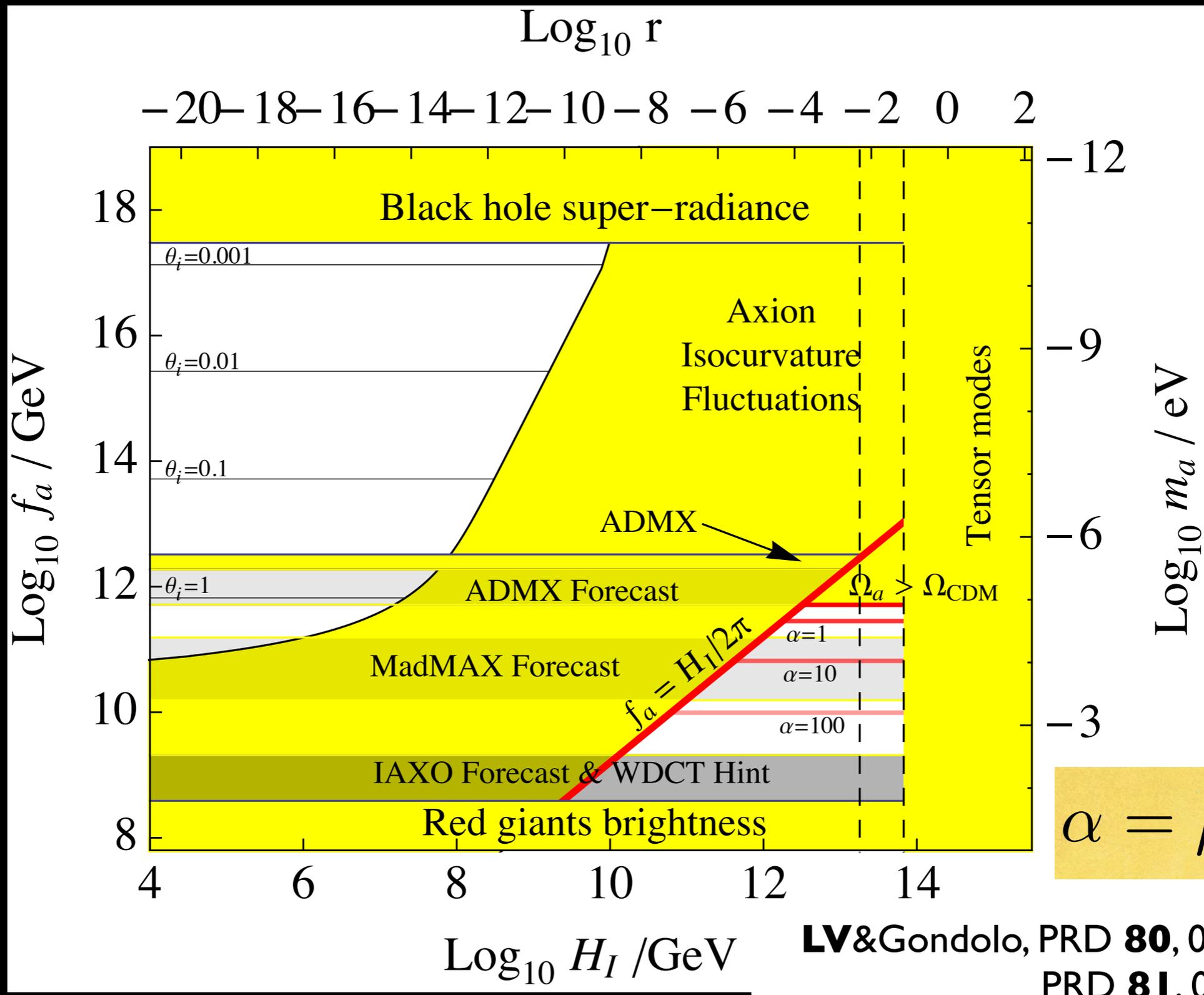


Destruction of the string-wall network



Vaquero+2018

The parameter space of the QCD axion



Wilczek, Turner '91; Beltran+ '06; Hertzberg+ '08; Wantz, Shellard '09

The parameter space of the QCD axion

One-parameter theory (the axion mass at zero temperature)

Let the simulations quantify the contribution from topological defects decay $\alpha = \rho_{\text{str}} / \rho_{\text{mis}}$

Fix the axion mass by requiring $\rho_A = \rho_{\text{CDM}}$

End of the story? Not really....

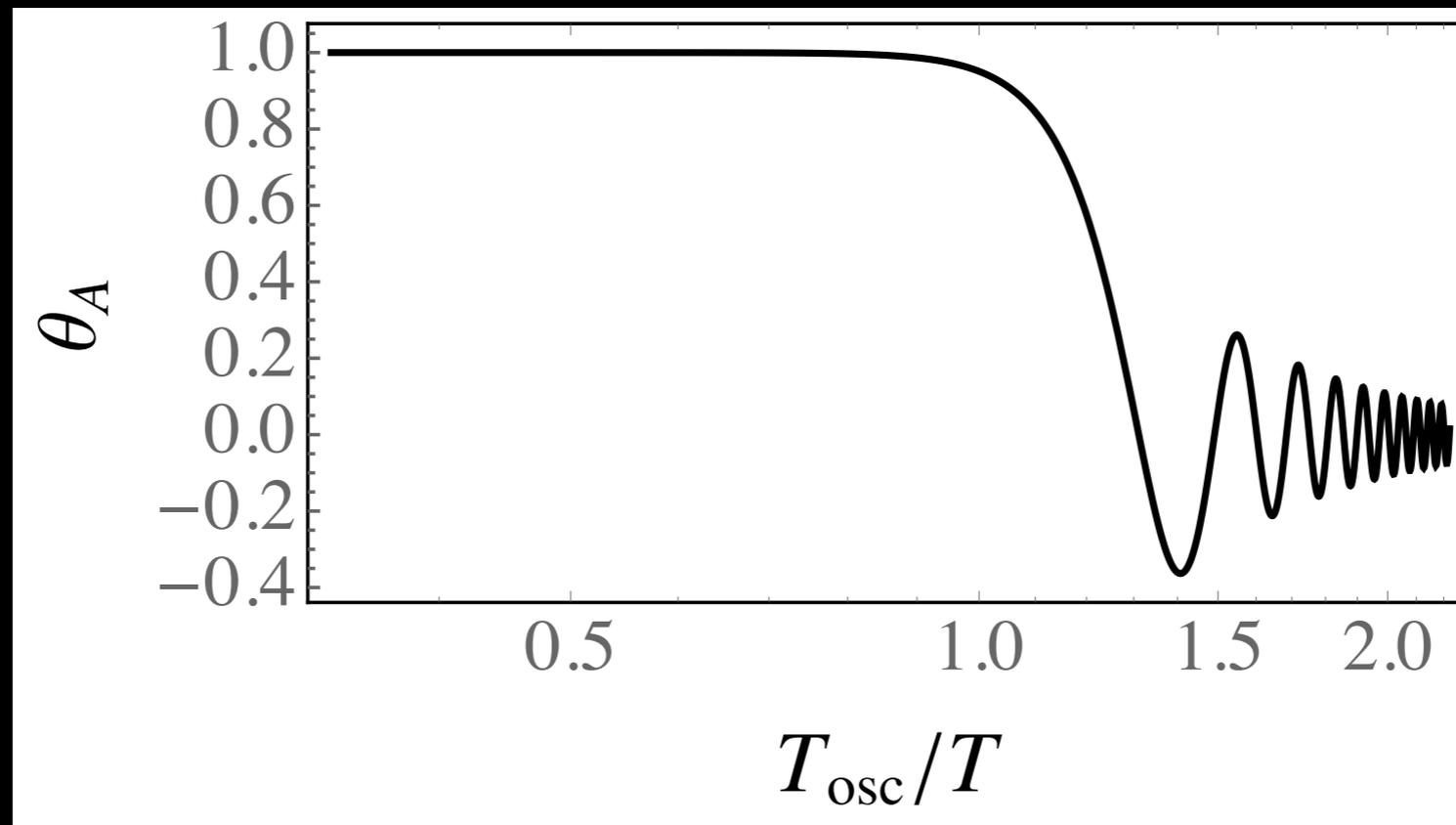
$$m_A(T_{\text{osc}}) \approx 3H(T_{\text{osc}})$$

Depends on particle physics

Depends on cosmology

The parameter space of the QCD axion

$$\ddot{\theta}_A + 3H\dot{\theta}_A + m_A^2(T) \sin \theta_A = 0$$



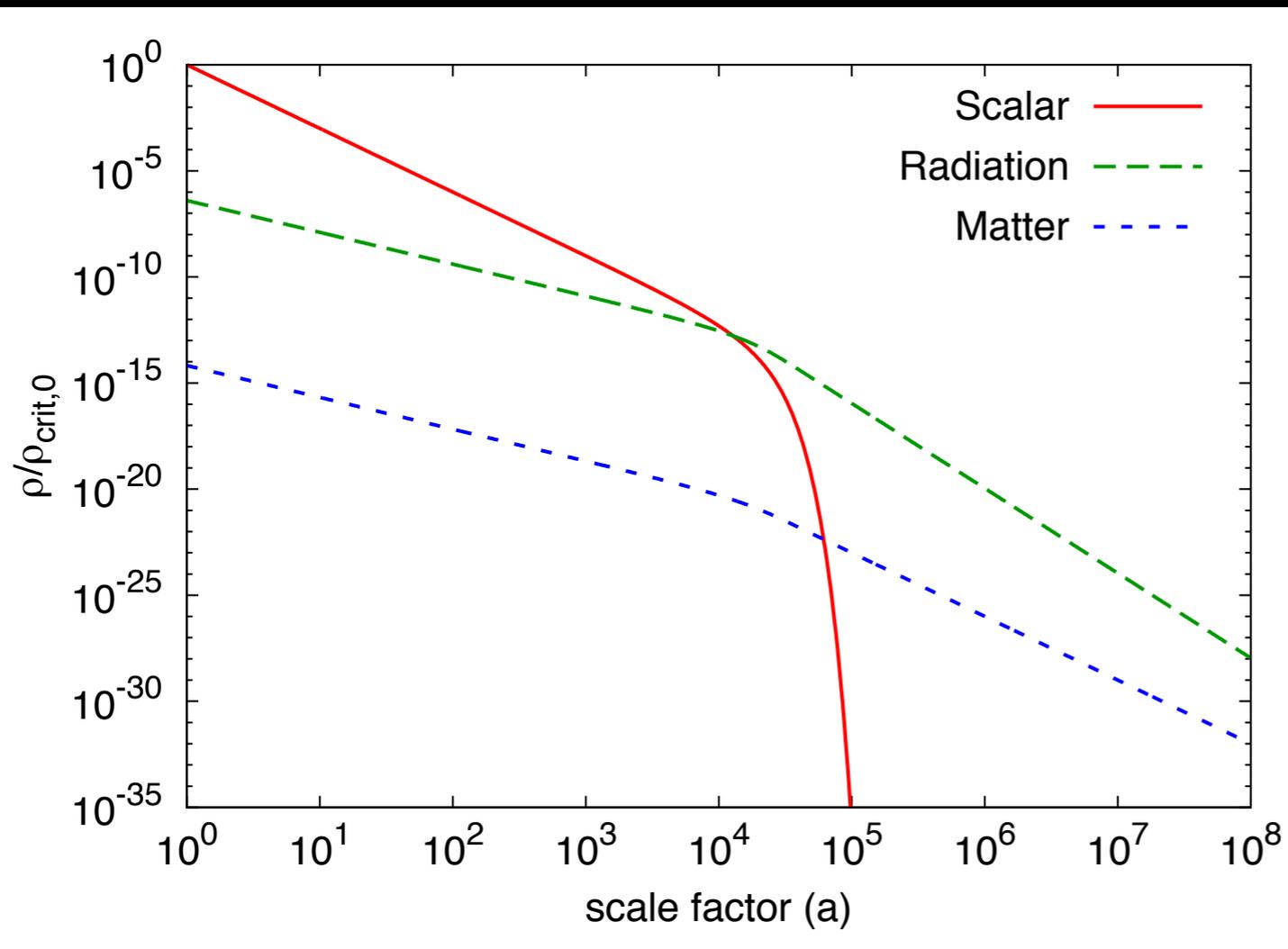
$$m_A(T_{\text{osc}}) \approx 3H(T_{\text{osc}})$$

Depends on particle physics

Depends on cosmology

Non-Standard cosmological model

Early matter-dominated (LRT) cosmology



Erickcek&Sigurdson 2011

$$\rho_\phi + 3H\rho_\phi = -\Gamma\rho_\phi$$

$$\rho_R + 4H\rho_R = b\Gamma\rho_\phi$$

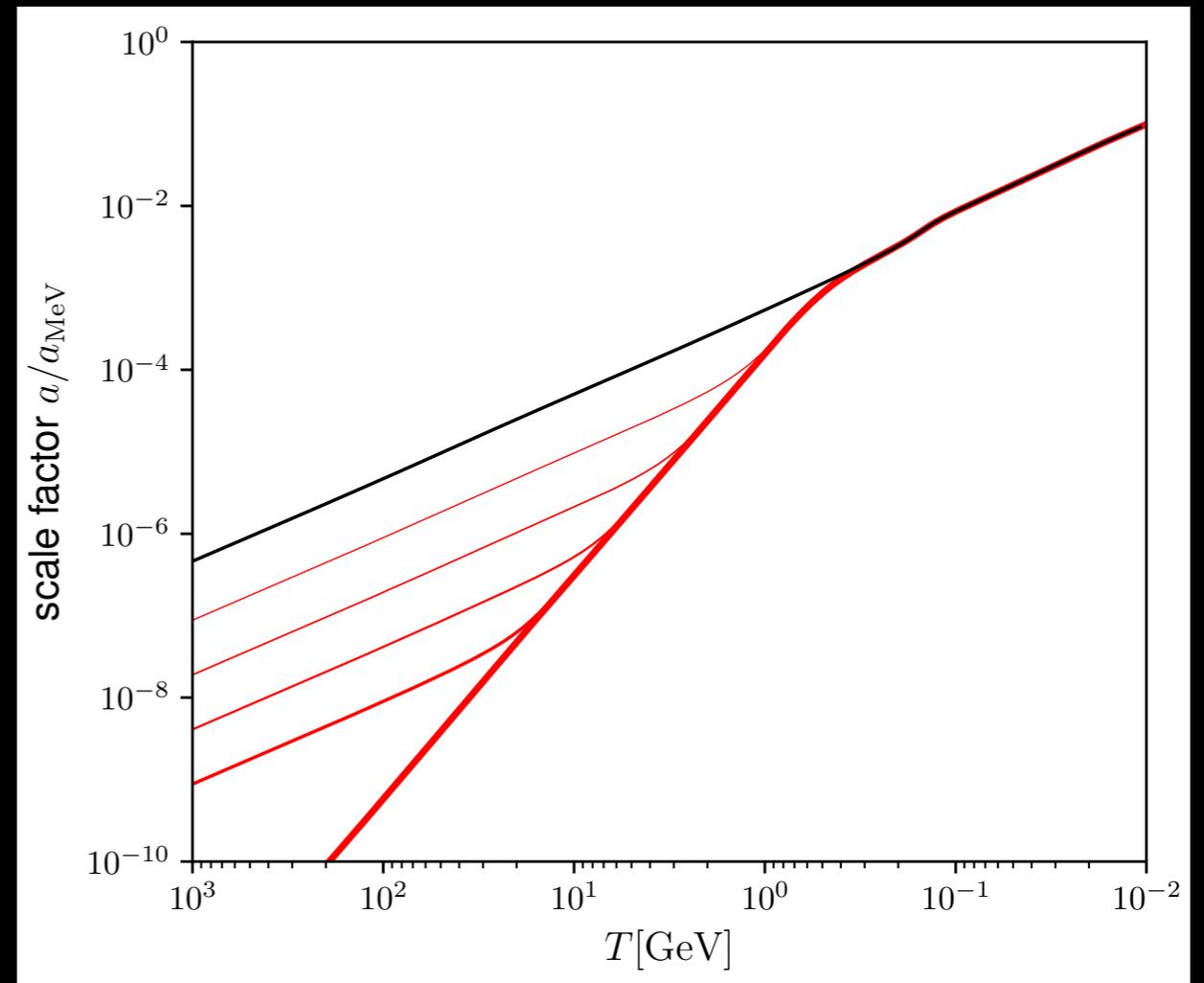
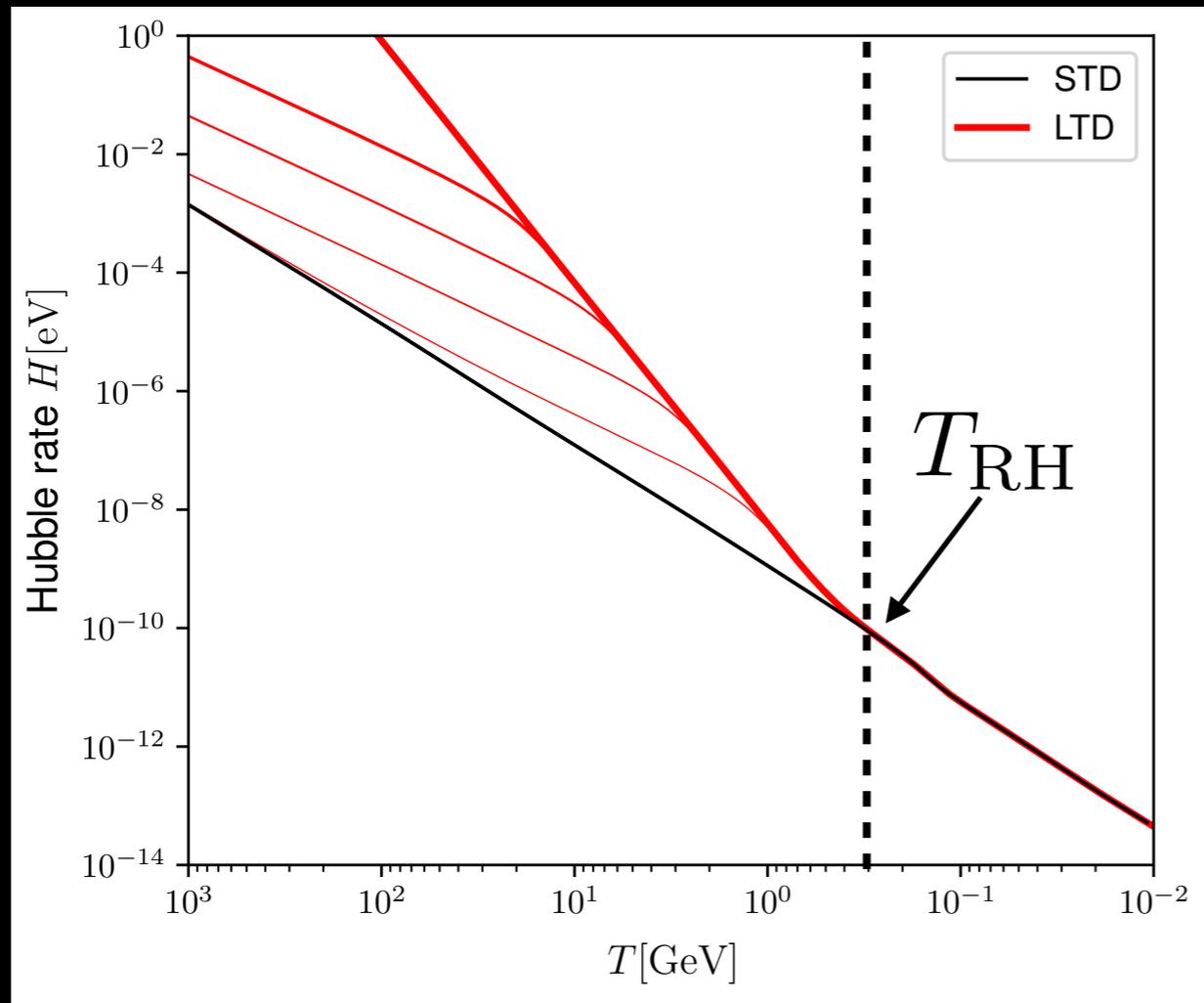
$$\rho_\psi + 3H\rho_\psi = (1 - b)\Gamma\rho_\phi$$

Structures grow linearly....

Non-Standard cosmological model

Early matter-dominated (LRT) cosmology

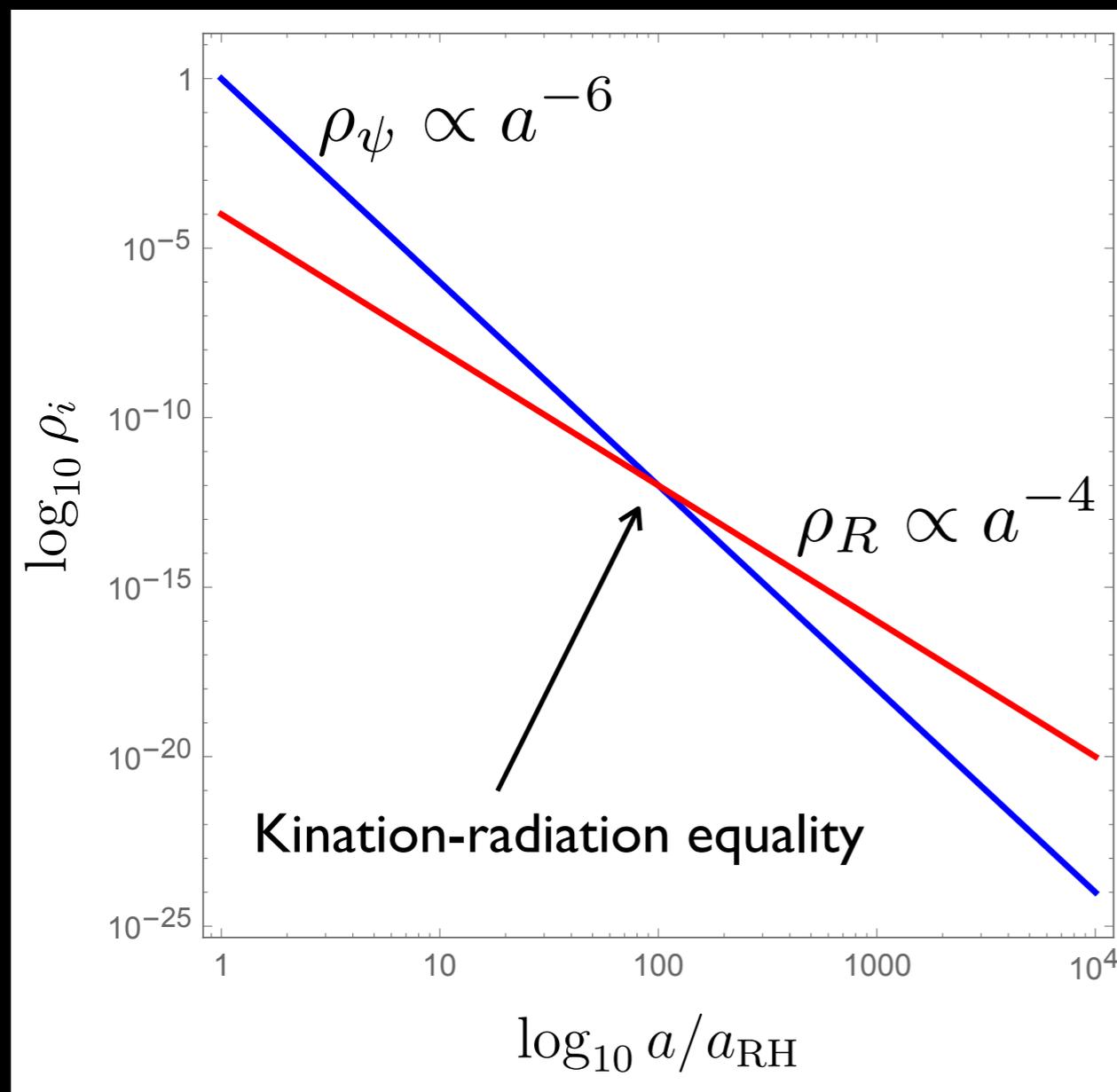
See [LV & Redondo 1808.01879](#)



$$a \propto T^{-8/3} \text{ during LRT}$$

Modified cosmologies

Early Kination cosmology



$$\mathcal{L} = \frac{1}{2} \dot{\psi}^2 - V(\psi)$$

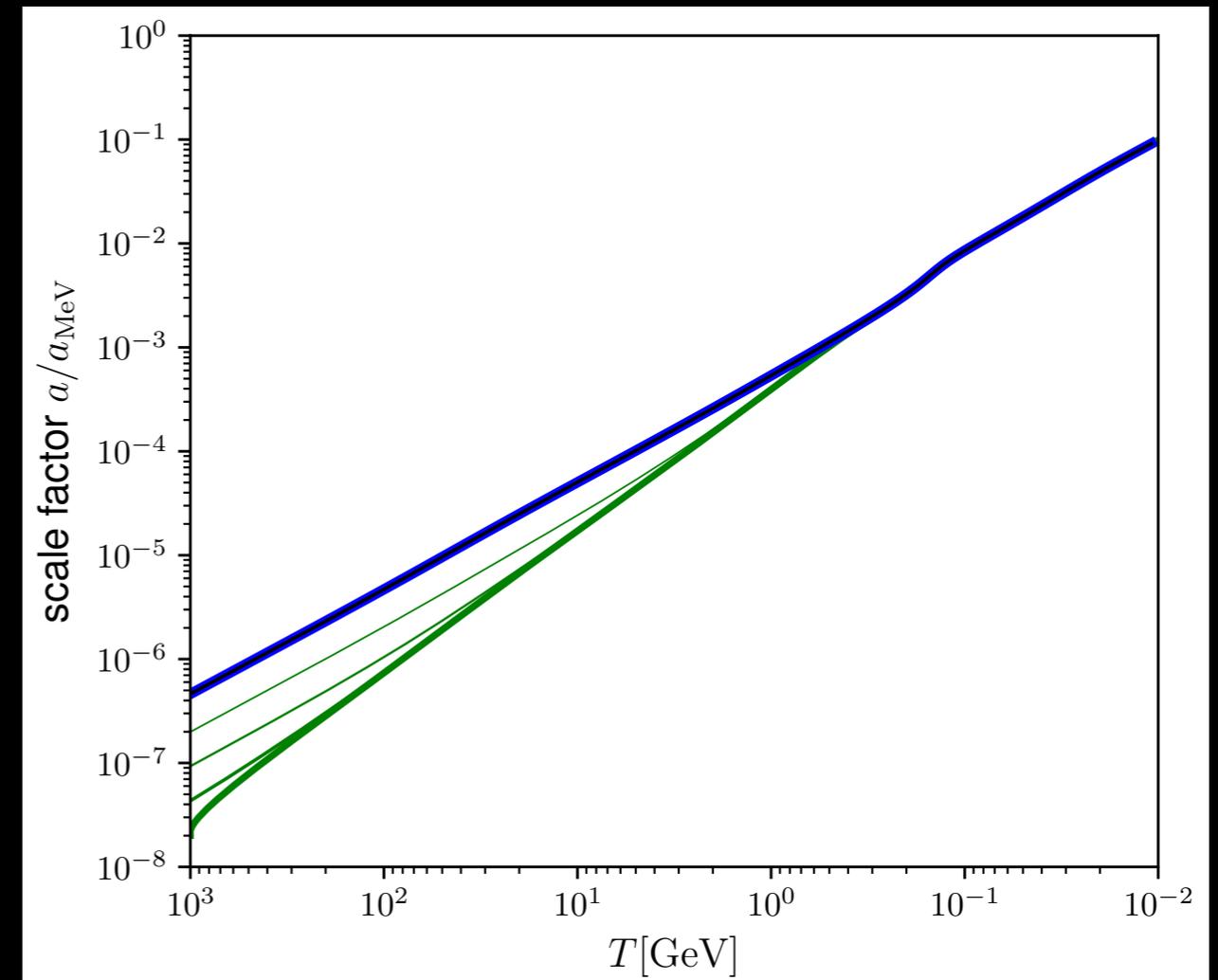
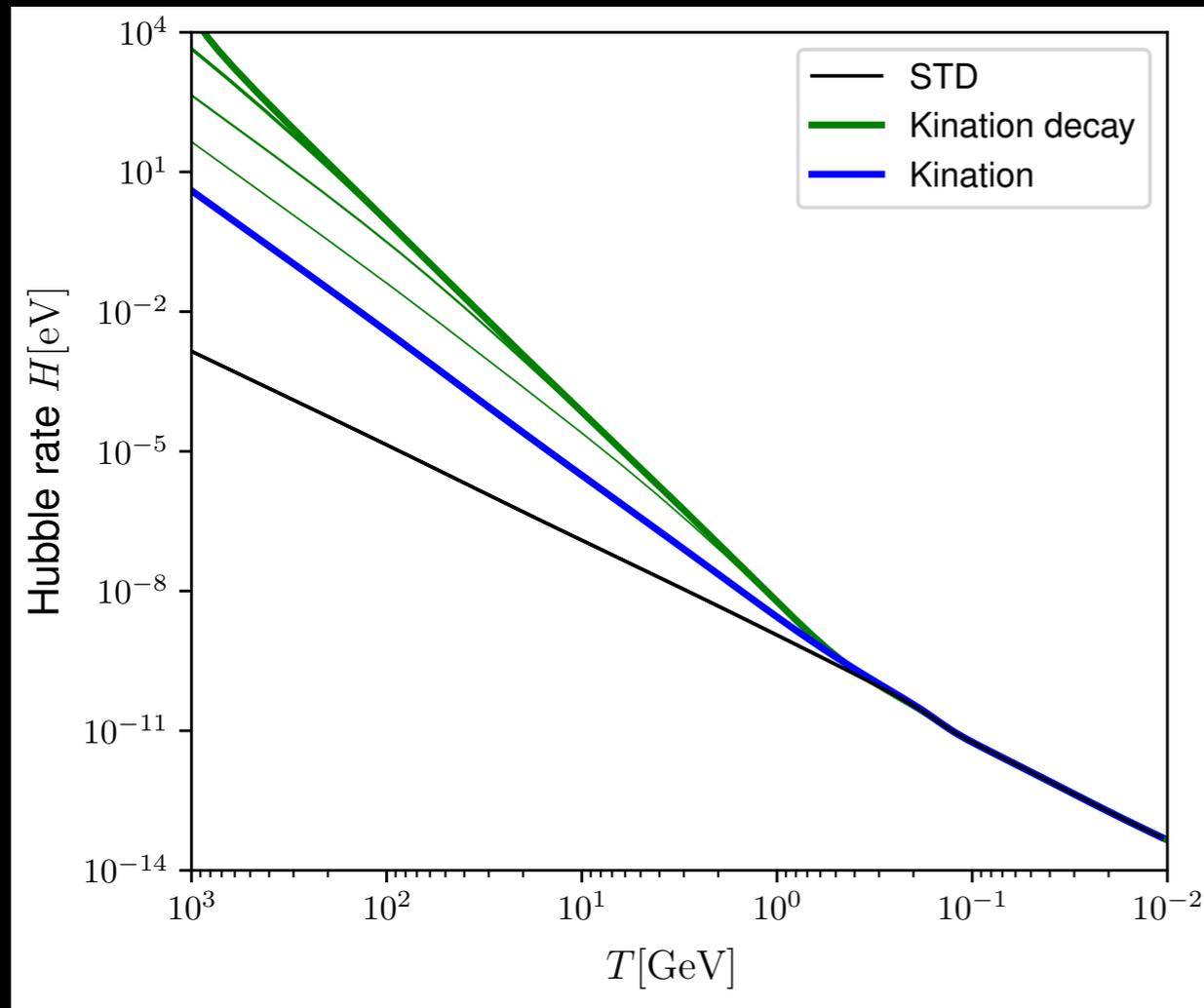
$$w_\psi = \frac{\frac{1}{2} \dot{\psi}^2 - V(\psi)}{\frac{1}{2} \dot{\psi}^2 + V(\psi)} \approx 1$$

$$\rho_\psi \propto a^{-3(1+w_\psi)}$$

Non-Standard cosmological model

Early Kination cosmology (with or without decay!)

See [LV & Redondo 1808.01879](#)



$a \propto T^{-4/3}$ during Kination Decay

Non-Standard cosmological model

In general we consider

$$\frac{d\rho_\phi}{da} + 3(1 + w_{\text{eff}})\rho_\phi = -\frac{\Gamma_\phi}{H}\rho_\phi$$

Two new parameters

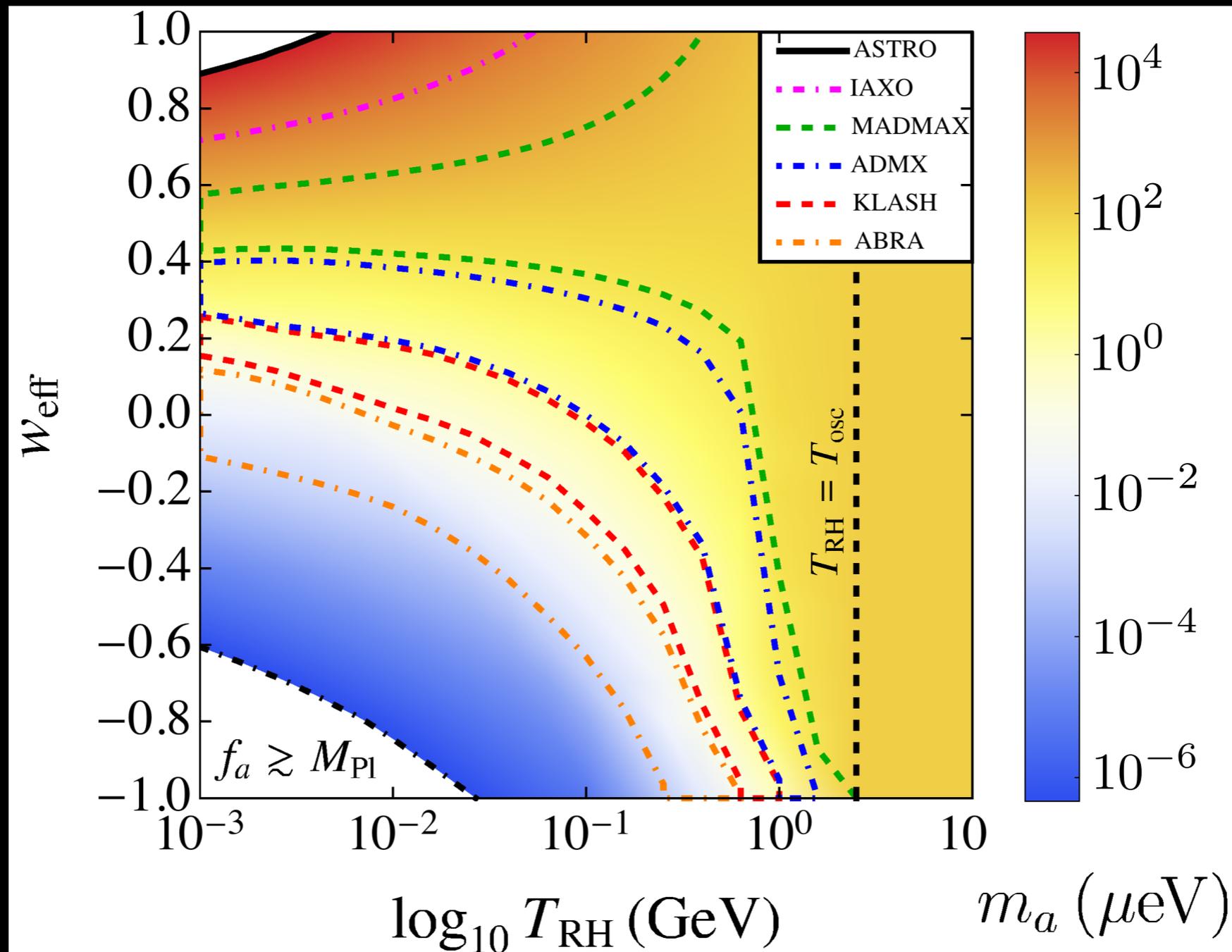
$$\frac{d\rho_R}{da} + 3(1 + w_R)\rho_R = \frac{\Gamma_\phi}{H}\rho_\phi$$

$\{w_{\text{eff}}, T_{\text{RH}}\}$

The axion “feels” the effects of the NSC if
field oscillations start sufficiently early

$$T_{\text{osc}} > T_{\text{RH}}$$

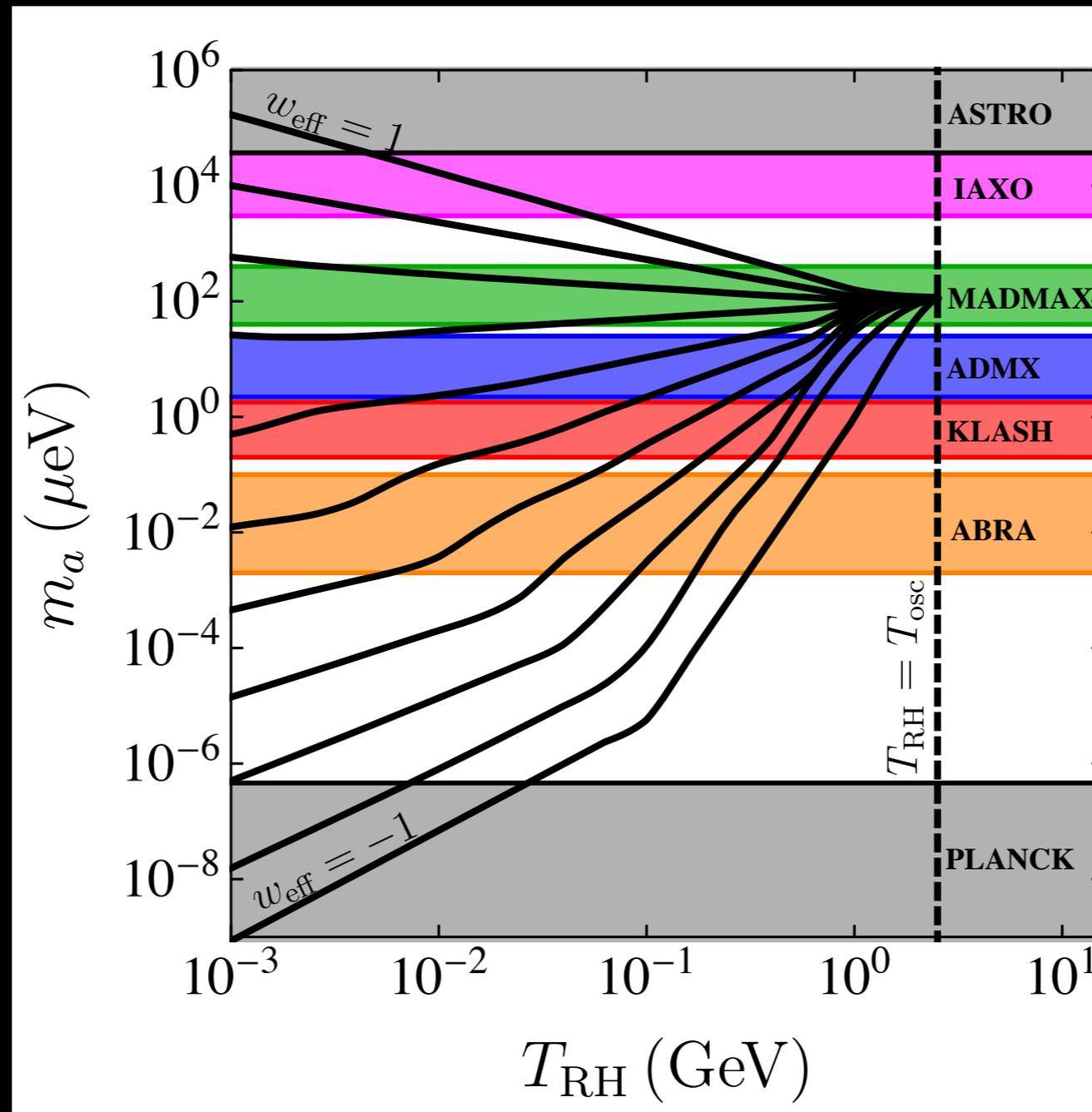
The dark matter axion mass



Nicklas Ramberg, & LV, 1904.05707 (out today!!)

<https://github.com/lucavisinelli/Axion-NonStandard-Cosmologies>

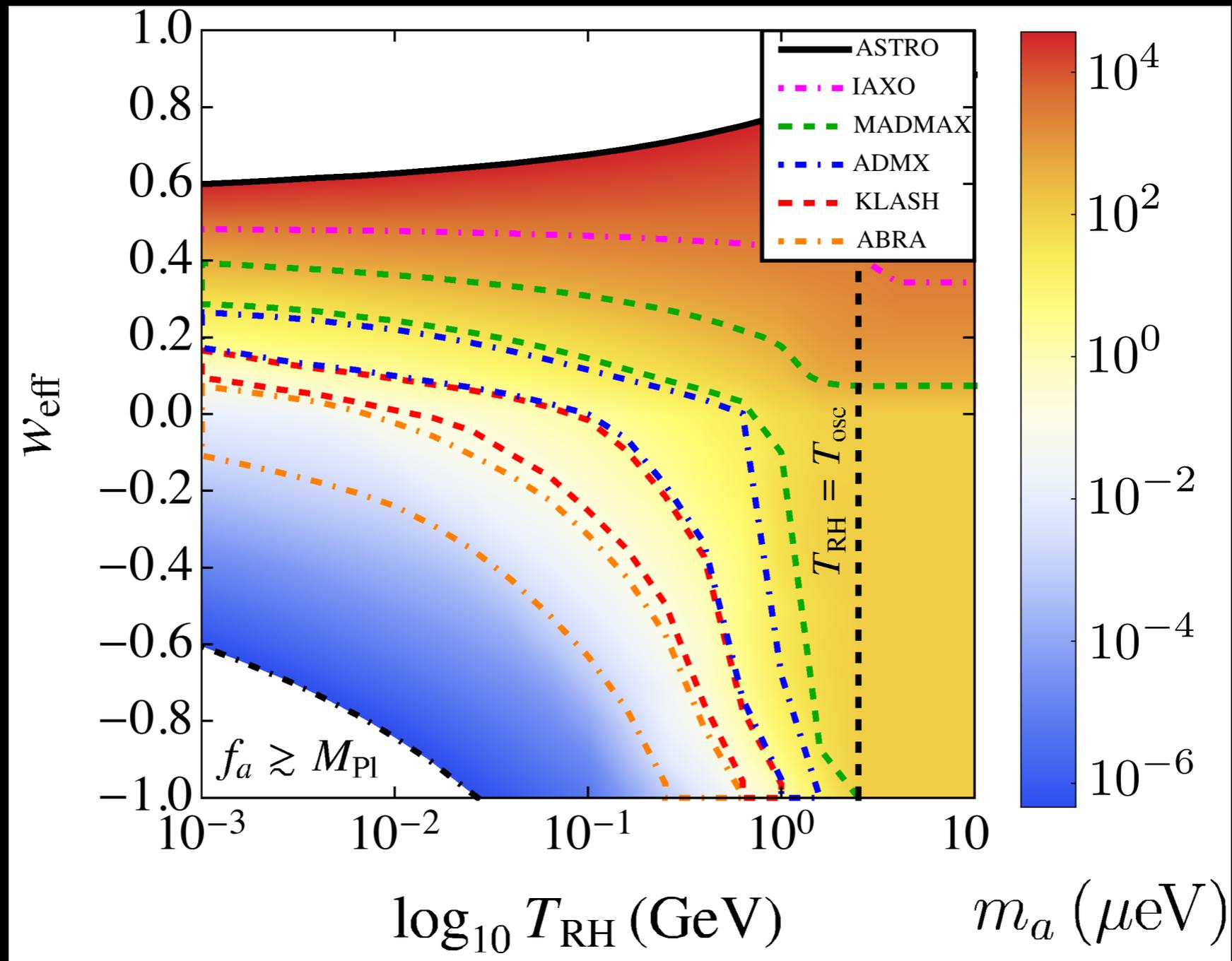
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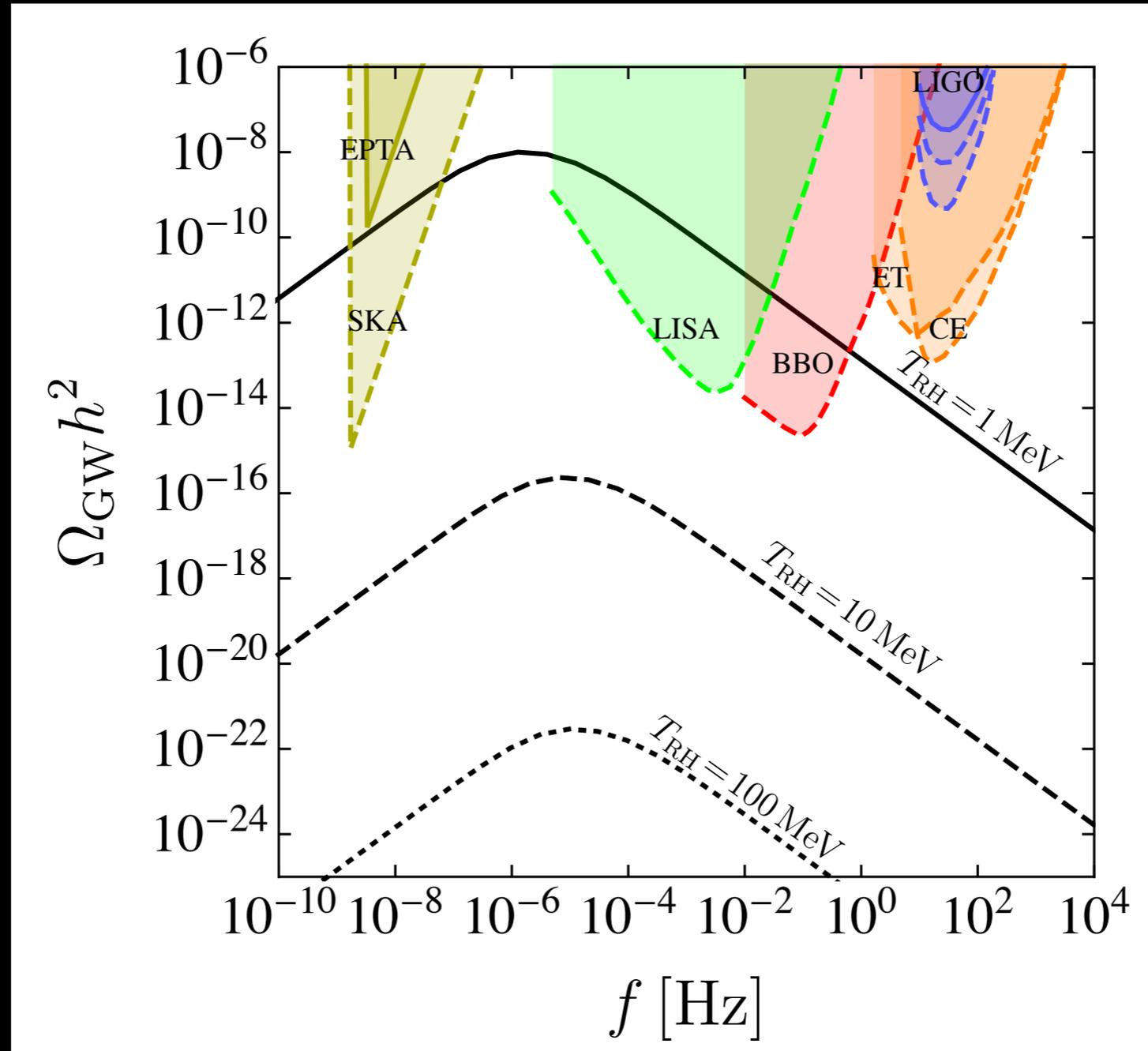
Including the effects of cosmic strings



Nicklas Ramberg, & LV, 1904.05707 (out today!!)

<https://github.com/lucavisinelli/Axion-NonStandard-Cosmologies>

GW from axionic string

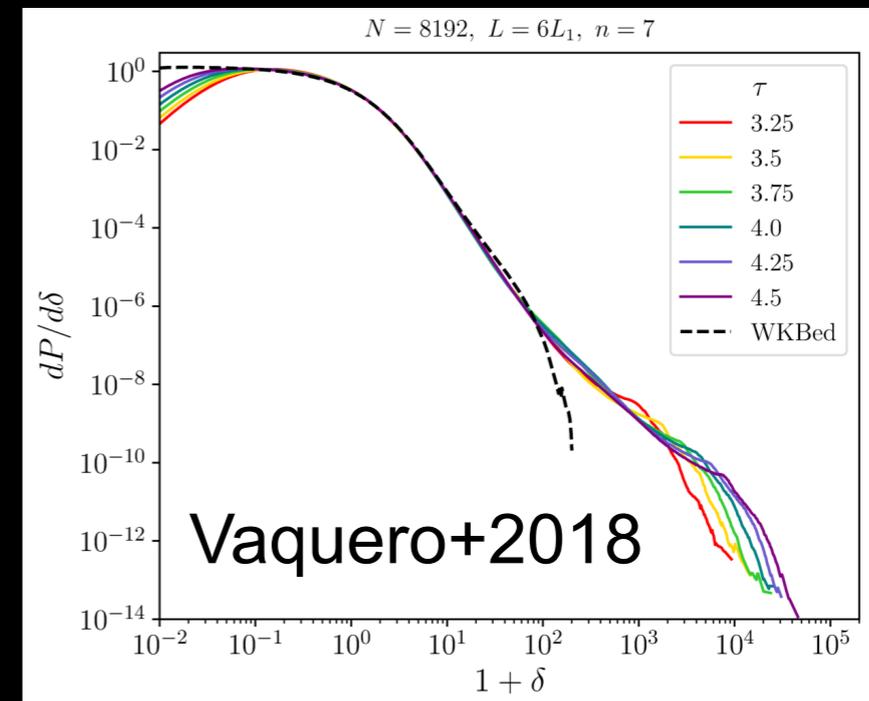
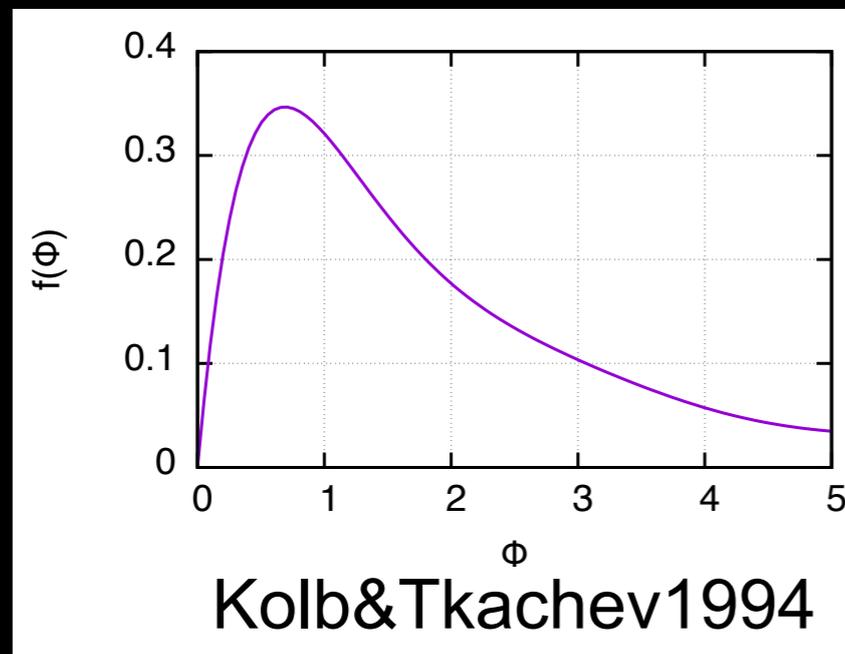


Nicklas Ramberg, & LV, 1904.05707 (out today!!)

<https://github.com/lucavisinelli/Axion-NonStandard-Cosmologies>

Compact objects

Regions with overdensities $\Phi = \delta\rho/\rho$



collapse at temperature $T_{\text{collapse}} = \Phi T_{\text{eq}}$

Density of miniclusters $\rho \sim 140(1 + \Phi)\Phi^3 \rho_{\text{eq}}$

See **LV** & Redondo 1808.01879

Power injection at very small scales

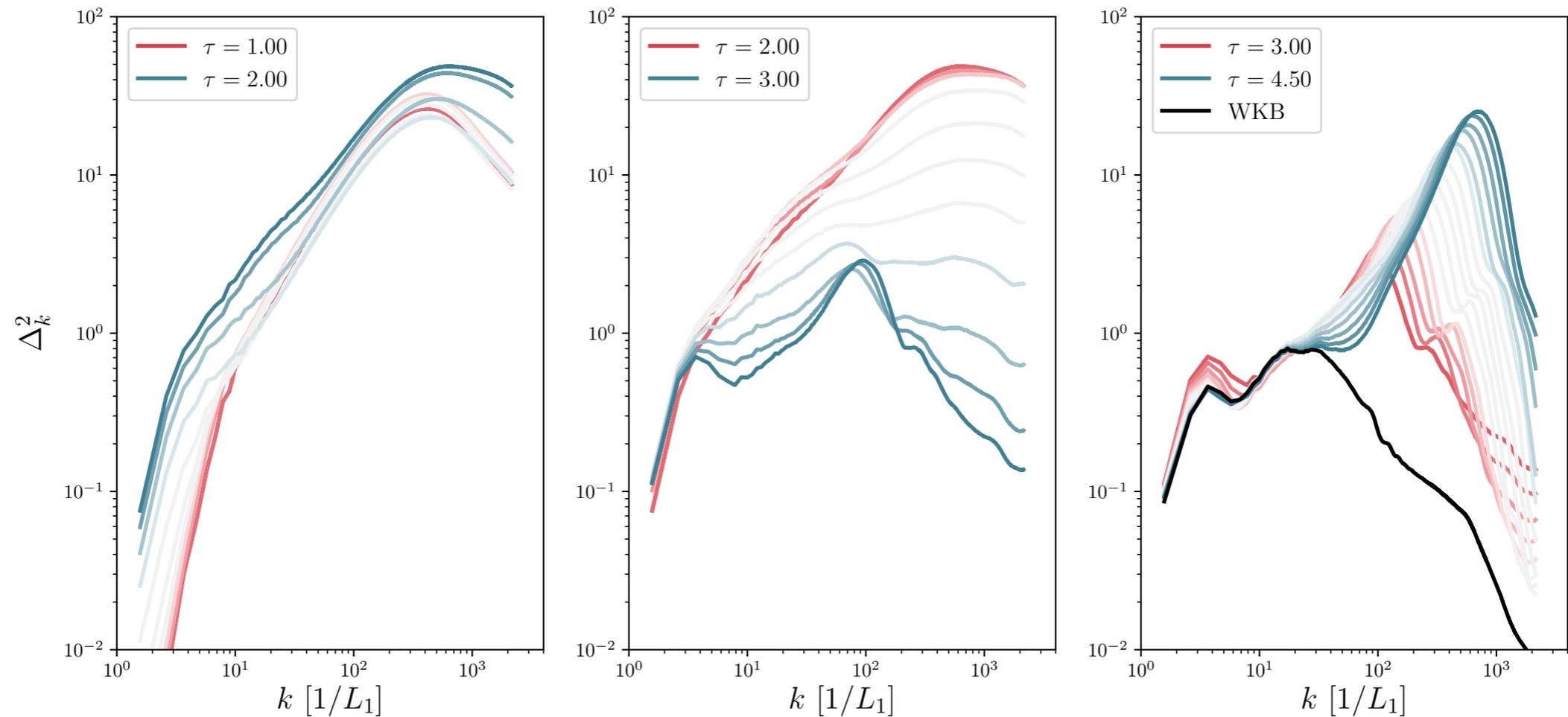


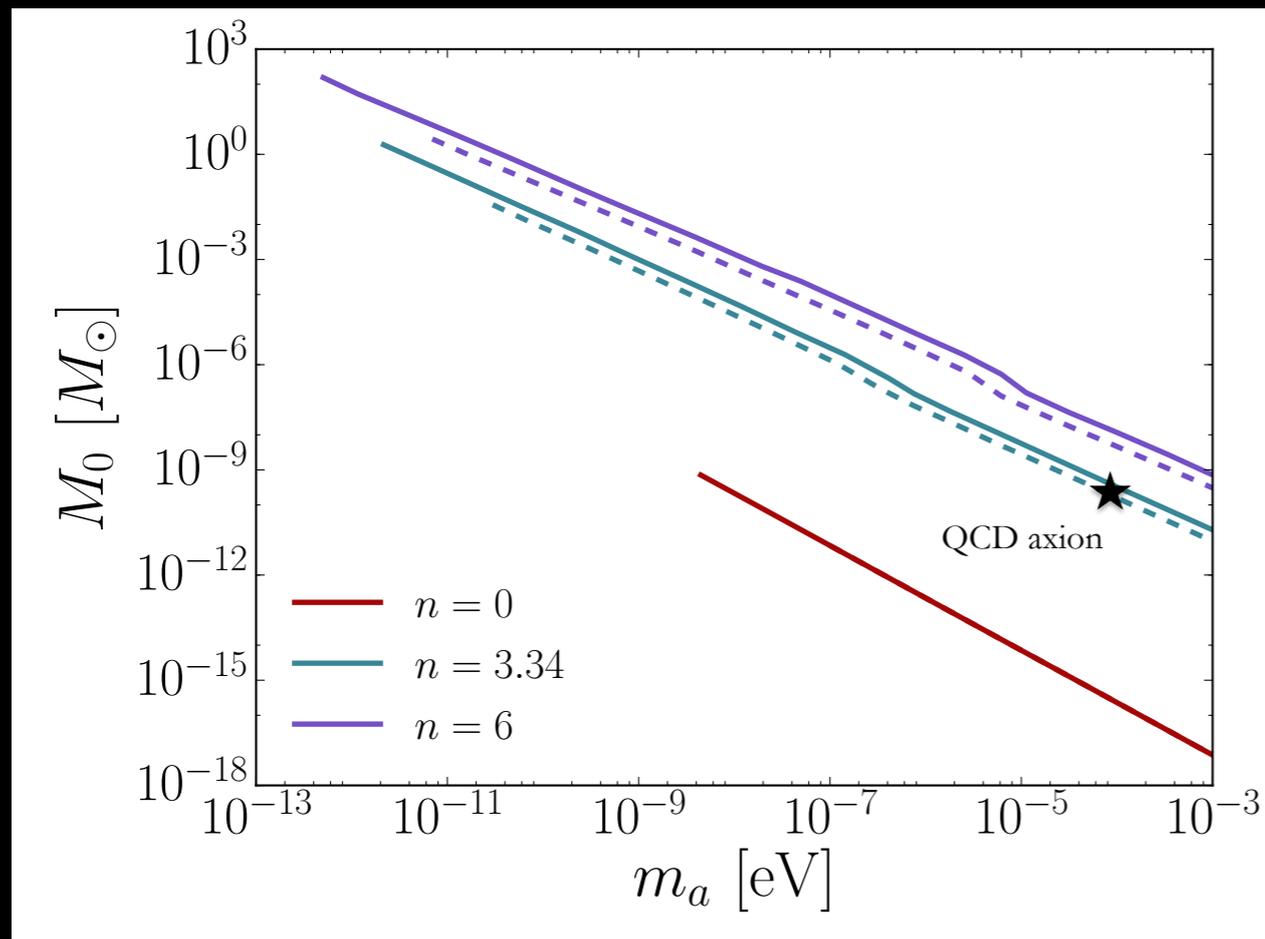
Figure 9: Time evolution of the dimensionless variance of axion energy density fluctuation as a function of momenta. Results are shown for an average over $L = 6L_1$, $N = 8192$ and $n = 7$ simulations. Different lines show the time evolution. For simplicity the legends quotes only the earliest and latest time shown in each plot, the remaining colors interpolate between these limits. The time difference between steps is $\Delta\tau = 0.1$. The three plots show the evolution through the three periods of our simulation: axions with strings, network destruction, non-relativistic period with axitons.

Vaquero+2018

Axion miniclusters

Mass $M_{\text{MC}} \sim 10^{-10} M_{\odot}$ (enclosed at H_{QCD}^{-1})

Radius $R_{\text{MC}} \sim 1 \text{ AU} / \Phi$. Virialization?

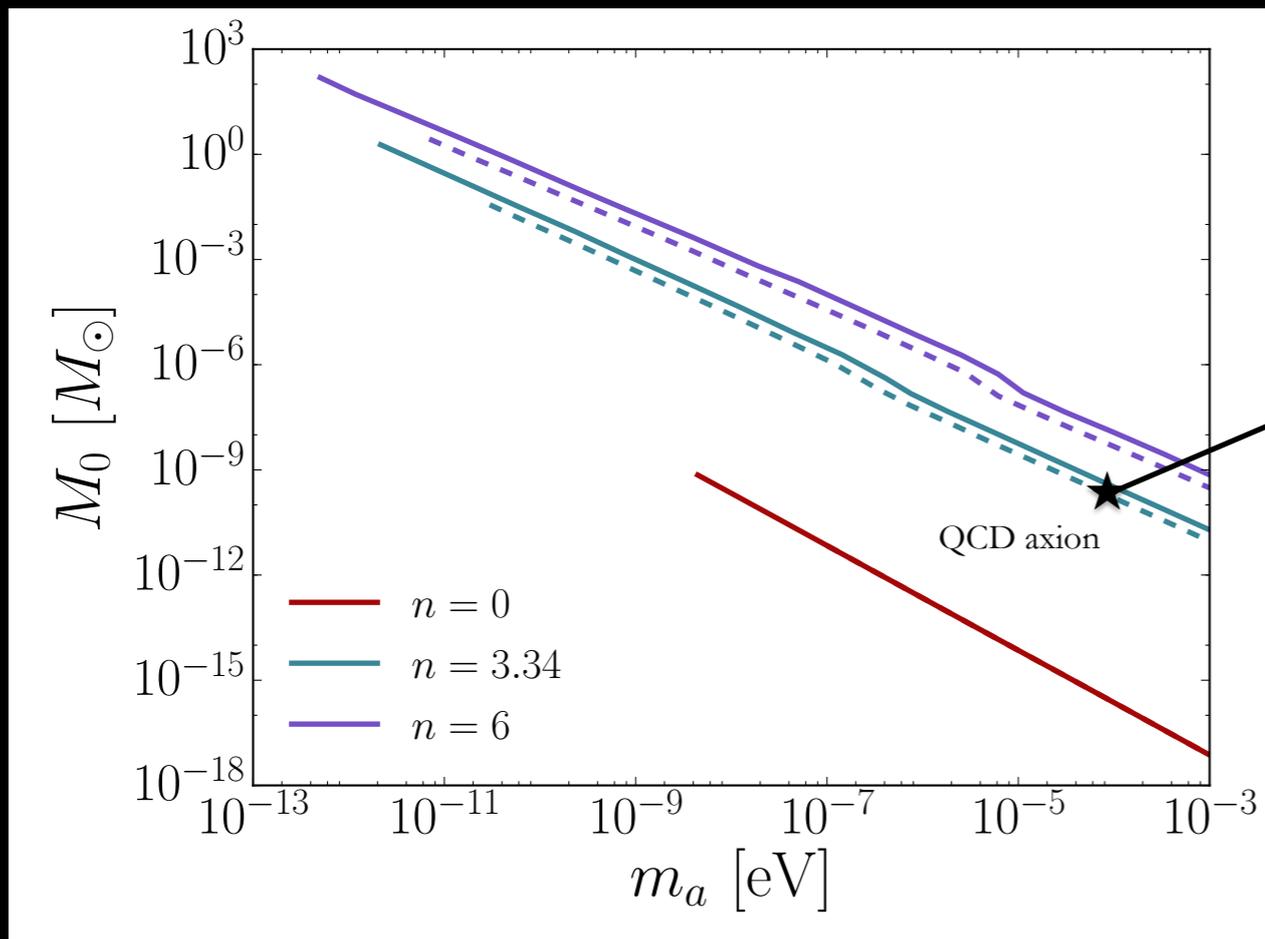


Fairbairn+2017

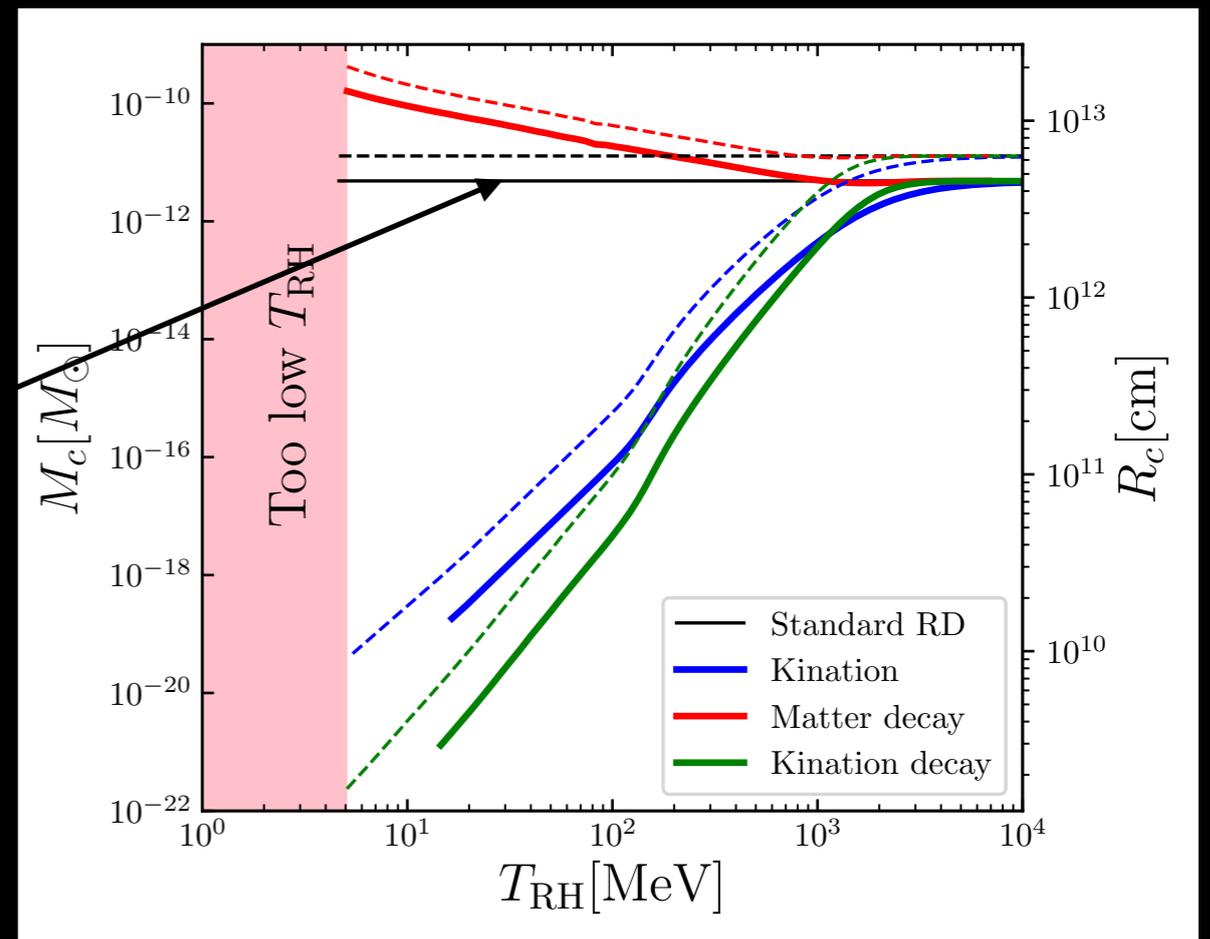
Axion miniclusters

Mass $M_{MC} \sim 10^{-10} M_{\odot}$ (enclosed at H_{QCD}^{-1})

Radius $R_{MC} \sim 1 \text{ AU} / \Phi$. Virialization?



Fairbairn+2017

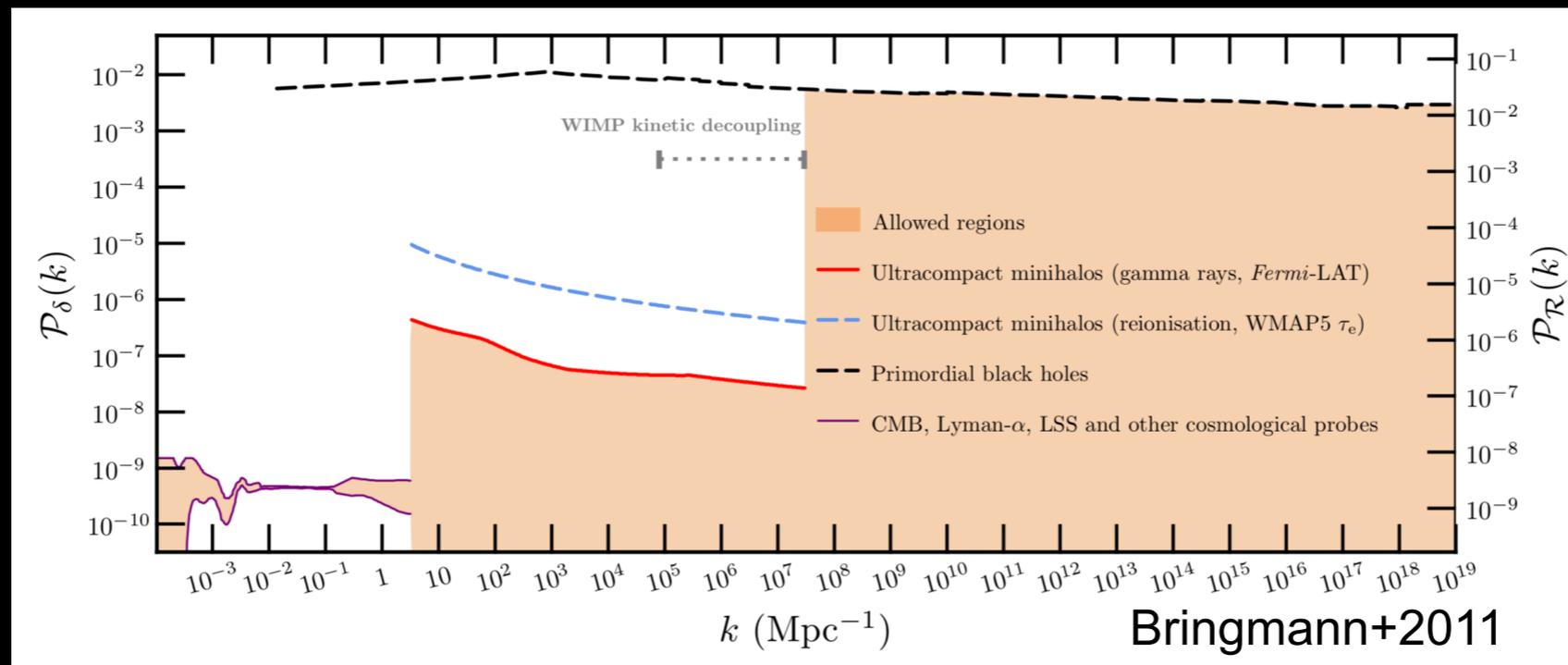


LV & Redondo 1808.01879

Axion miniclusters

Growth of axion perturbations during NSC at subhorizon

$$\ddot{\delta}_A + \left(2H + \frac{\dot{m}}{m} \right) \dot{\delta}_A - \frac{3}{2} H^2 \delta_\phi = 0$$



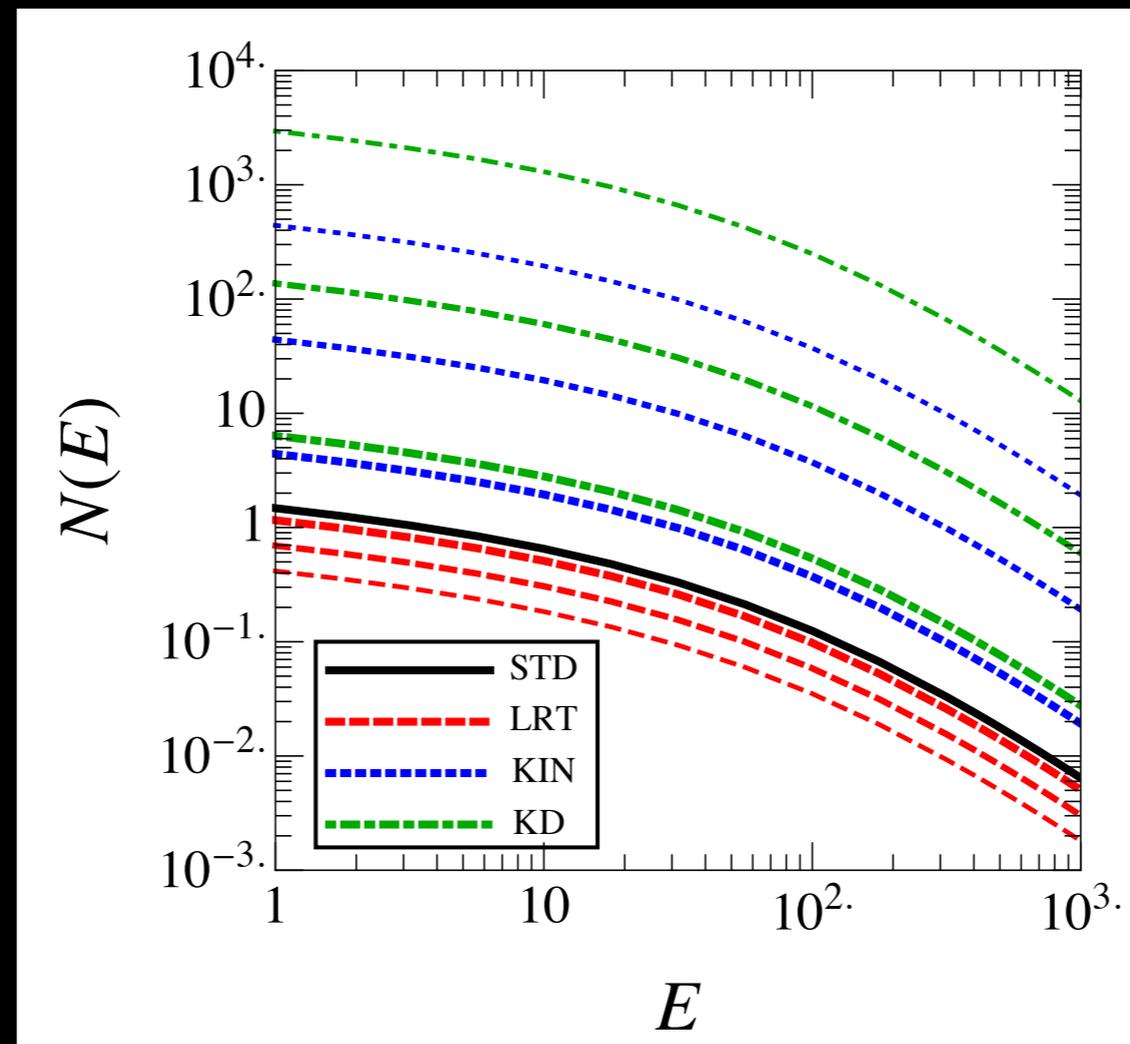
The smallest scale at which fluctuations become non-linear

$$k'_1 \approx k_1/30 \quad \text{or} \quad M'_c = M_{c,0} \left(\frac{k_1}{k'_1} \right)^3 \sim 10^{-6} M_\odot$$

Survival of the minicluster

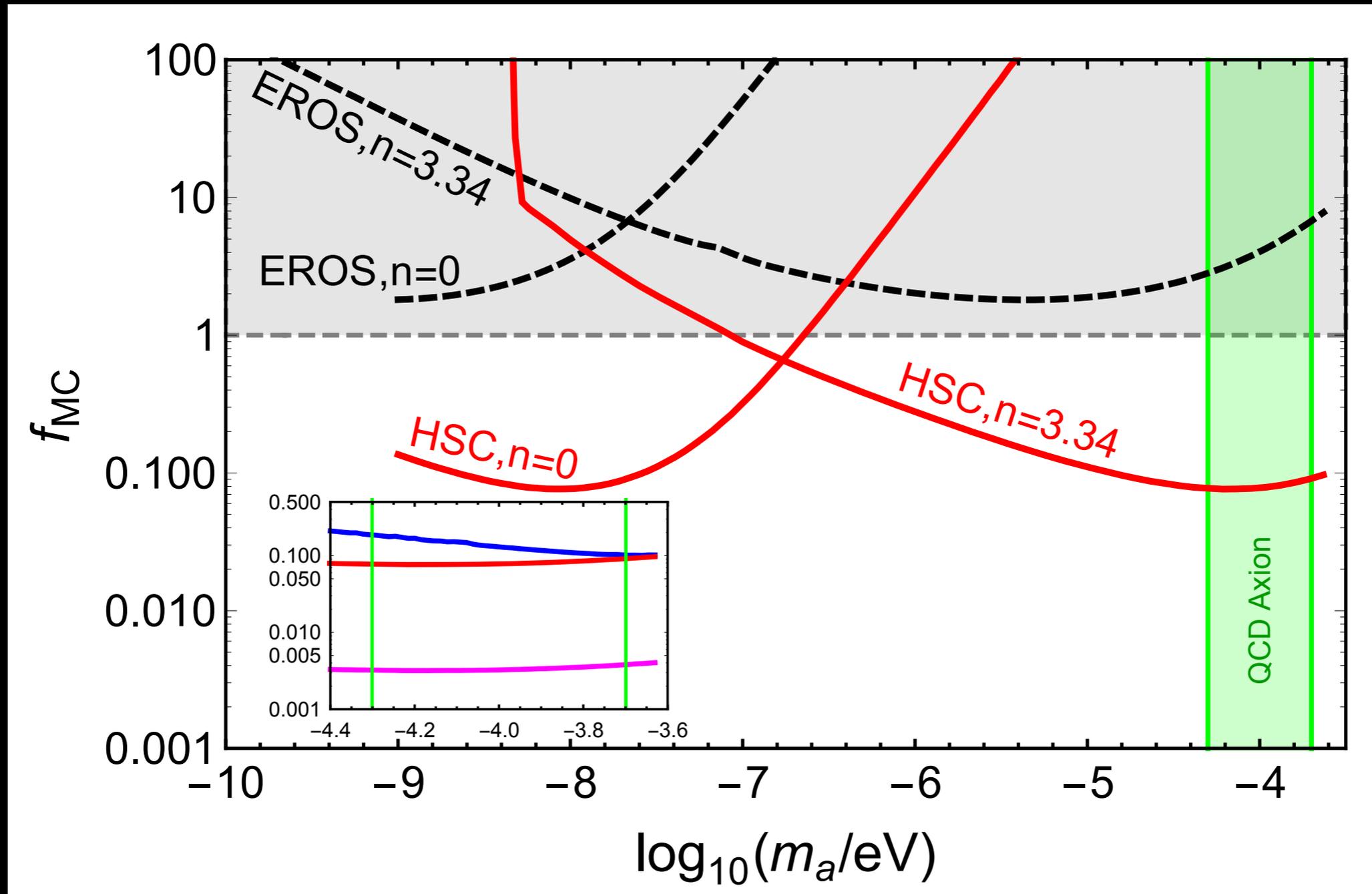
Disruption probability over a Galactic year $p \sim 2\% \Phi^{-3/2} (1 + \Phi)^{-1/2}$

Disrupted miniclusters form streams with detectable chance



Tinyakov+16; LV&Redondo18

Microlensing



Fairbairn+2017

Axion stars

What if R is comparable to $\lambda_{\text{de Broglie}}$?

$$\frac{M}{2} \left(\frac{\hbar}{m_a R} \right)^2 = \frac{3}{5} \frac{GM^2}{2R} \longrightarrow R \propto \frac{1}{M}$$

velocity dispersion $\sigma = \frac{\hbar}{m_a R} \sim 10^{-8}$

- Formation? Accretion? Disruption?
- Effects on structure formation?
- What happens when they collide?

Solitons made out of bosons

A bosonic field can arrange into a self-gravitating, compact, solitonic equilibrium configuration

The field must be oscillating: $\theta = \theta \cos mt$

I) Beats Derrick theorem (prevents static solutions of non-linear KGE) [G.H.Derrick, J. Math. Phys. 5 1252 (1964)]

II) Applies to scalar bosons (no Noether current)

Solitons made out of bosons

Massive real scalar field $\phi = \phi(x)$

Self-gravitating $G^{\mu\nu} = 8\pi T^{\mu\nu}(\phi)$

Lagrangian: $\mathcal{L} = \frac{1}{2} (\partial^\mu \phi) (\partial_\mu \phi) - V(\phi)$

Metric: $ds^2 = N^2(t, r) dt^2 - g^2(t, r) dr^2 - r^2 d\Omega^2$

Oscillons out of the axion field

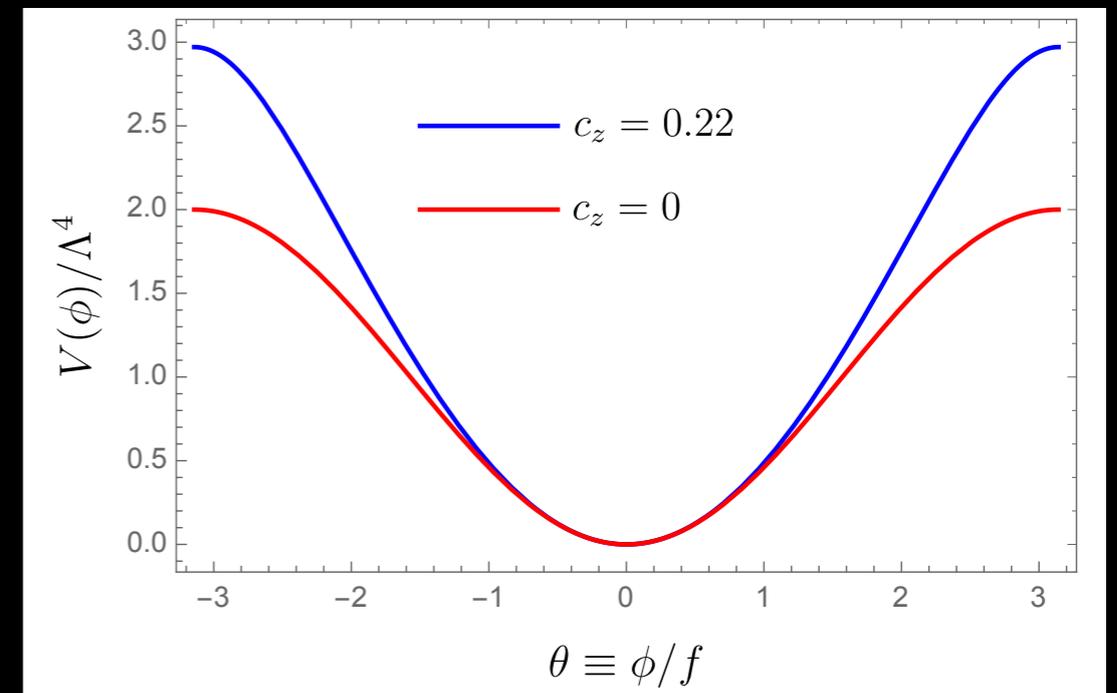
$$V(\phi) = \frac{\Lambda^4}{c_z} \left(1 - \sqrt{1 - 4c_z \sin^2 \frac{\phi}{2f}} \right)$$

Di Vecchia & Veneziano,
Nucl. Phys. B **171** 253 (1980);
Grilli di Cortona *et al.*
JHEP **01** 034 (2016)

f Axion decay constant

$$\Lambda = 75.5 \text{ MeV}$$

$$c_z \approx \frac{z}{(1+z)^2} \approx 0.22$$



Solitons made out of bosons

Oscillating solution $\phi = f \Theta(r) \cos(\omega t)$

Non-relativistic regime when $|\phi| \ll f$ (or $|\theta| \ll 1$)

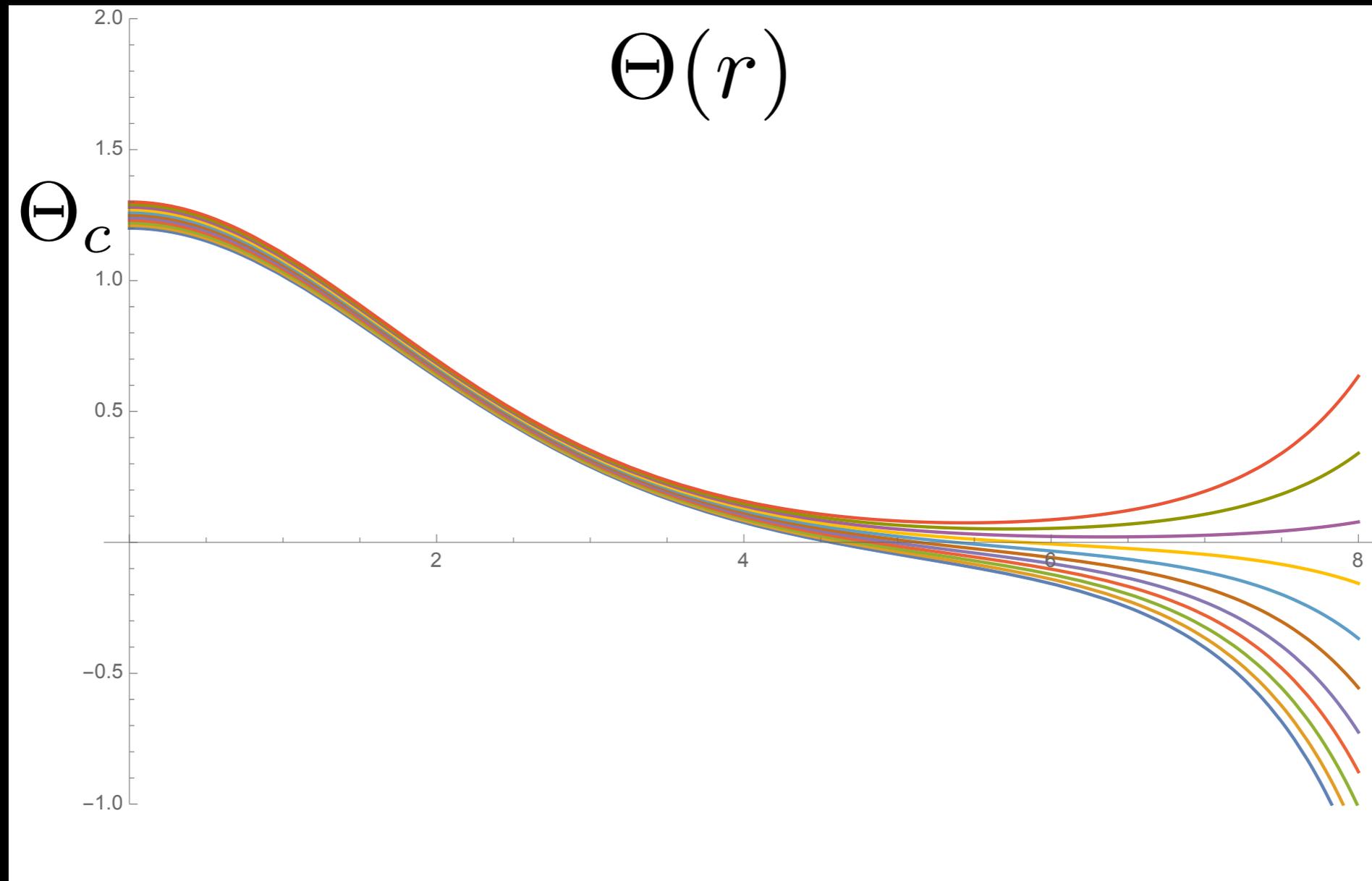
Also, $\omega \approx m$ ($= \Lambda^2 / f$)

Poisson equation + Schrödinger equation

(From Einstein eq.)

(From Klein-Gordon eq.)

Solving by shooting method



$$M = 4\pi \int_0^{+\infty} r^2 \phi^2(r) dr \quad 0.9M = 4\pi \int_0^{R_{90}} r^2 \phi^2(r) dr$$

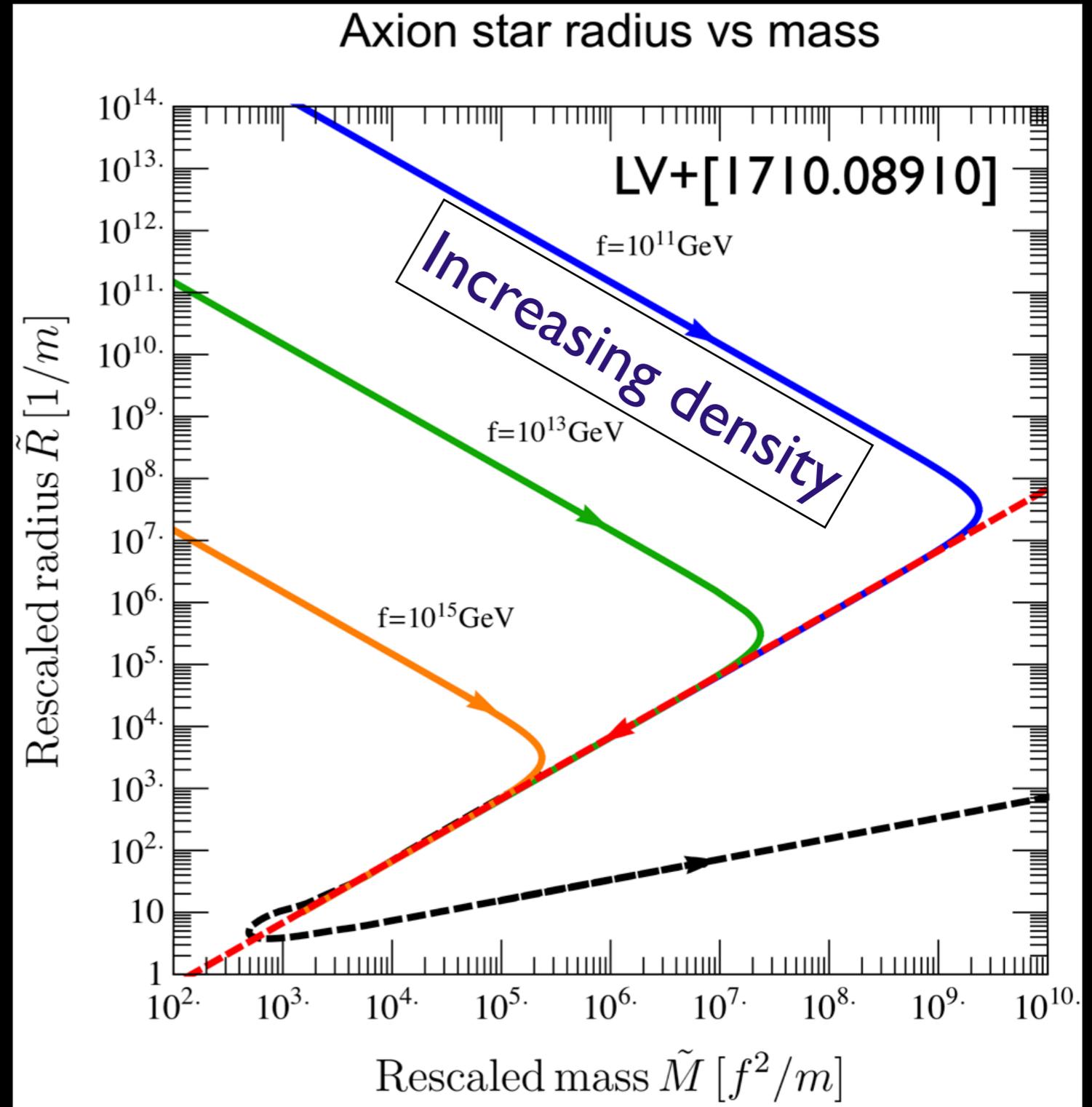
Mass-radius of an axion star

Natural mass and radius scales:

$$\frac{f^2}{m} = 3 \times 10^{-20} M_{\odot} \left(\frac{10^{-5} \text{ eV}}{m} \right)^3$$

$$\frac{1}{m} = 3 \times 10^{-11} R_{\odot} \left(\frac{10^{-5} \text{ eV}}{m} \right)$$

Three 'branches'



Mass-radius of an axion star

“Dilute” branch

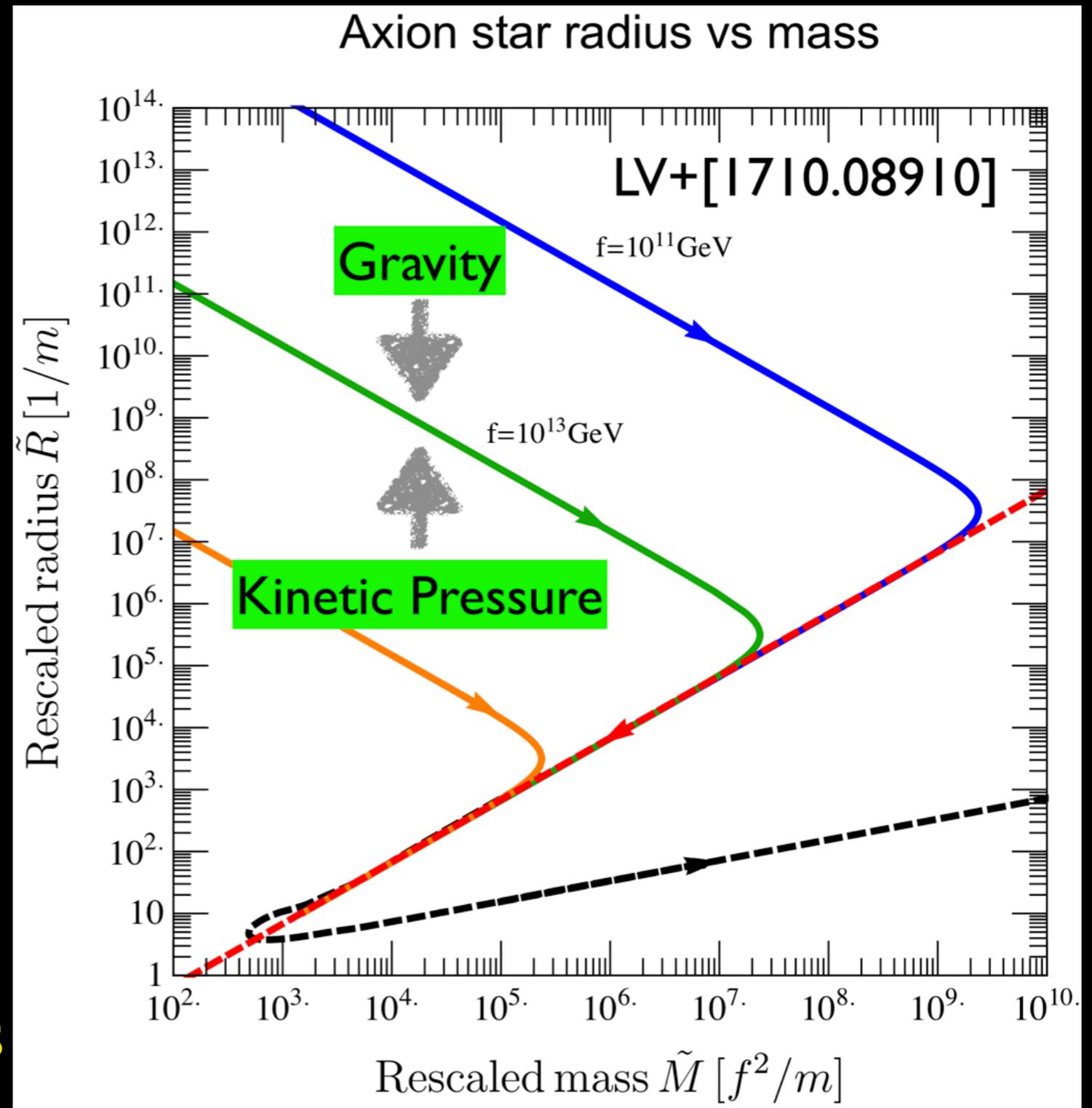
Relevant contributions:

- Kinetic pressure
- Gravity

$$U \sim \frac{M}{2} v^2 - \frac{GM^2}{R}$$

$$R \propto 1/M$$

Stable against perturbations



Mass-radius of an axion star

“Dilute” branch

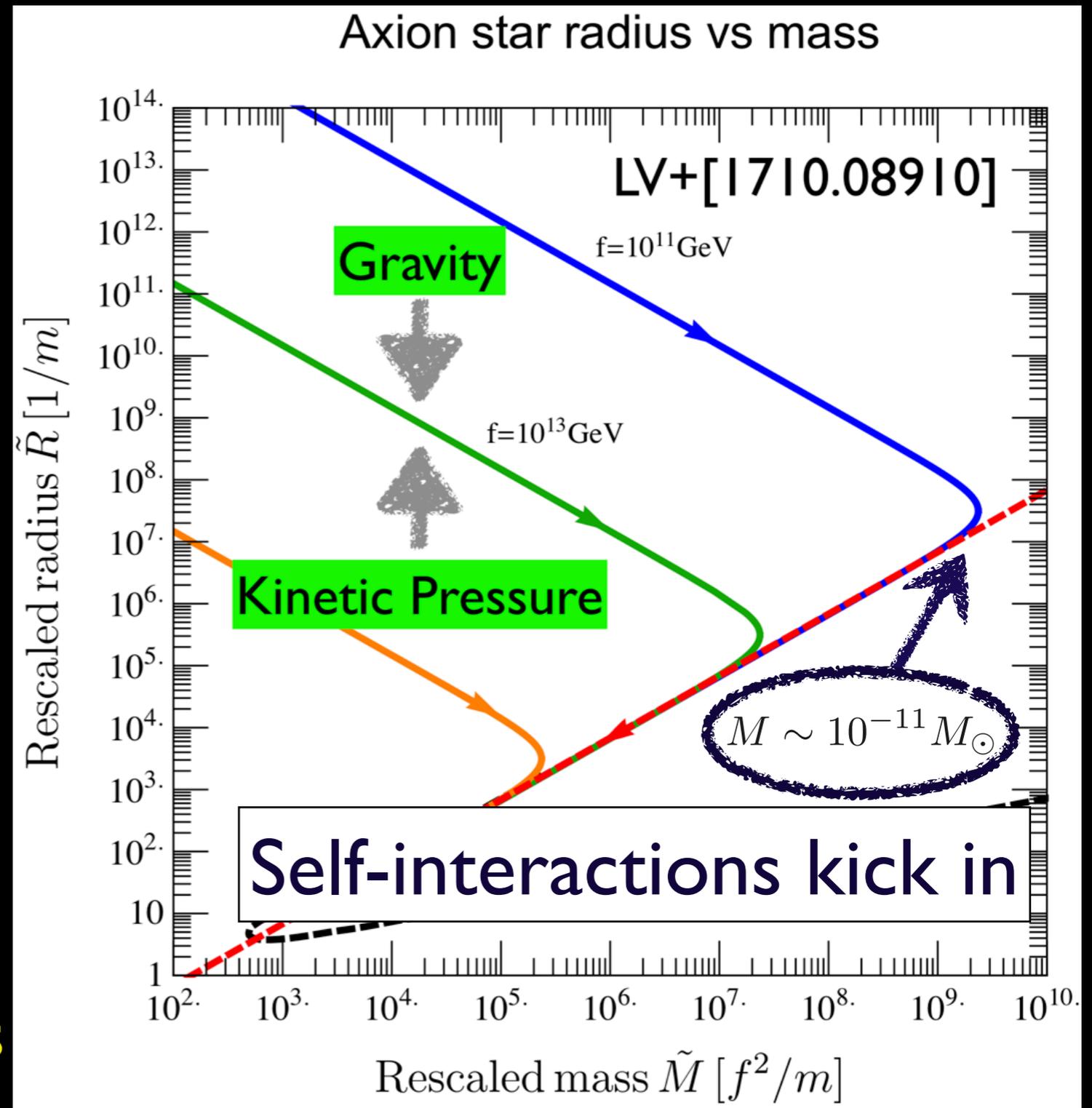
Relevant contributions:

- Kinetic pressure
- Gravity

$$U \sim \frac{M}{2} v^2 - \frac{GM^2}{R}$$

$$R \propto 1/M$$

Stable against perturbations



Mass-radius of an axion star

“Critical” branch

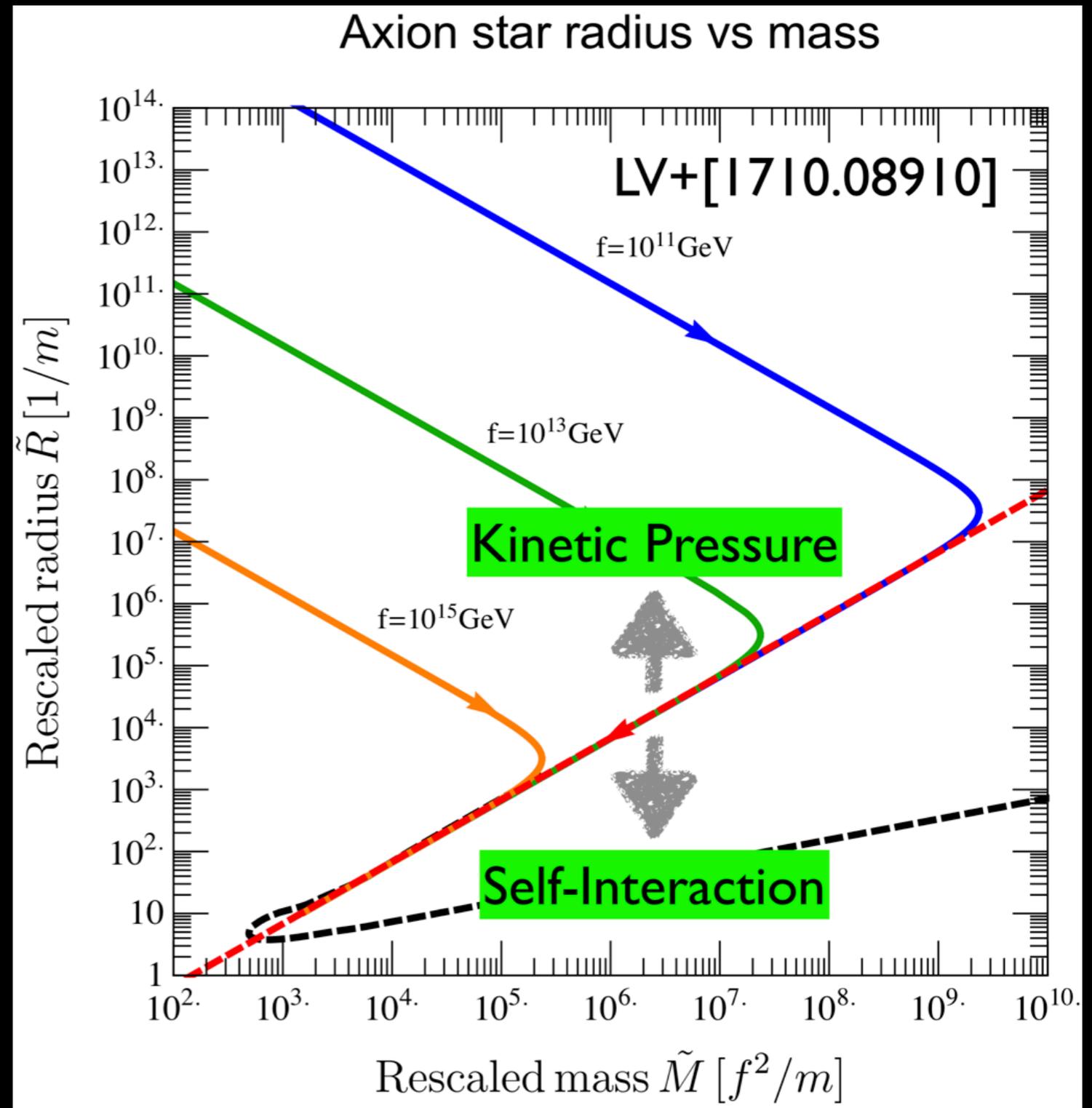
Relevant contributions:

- Kinetic pressure
- Quartic interaction

$$U \sim \frac{M}{2} v^2 - \Lambda^4 \Theta_c^4 R^3$$

$$R \propto M$$

Not stable against perturbations



Mass-radius of an axion star

“Dense” branch

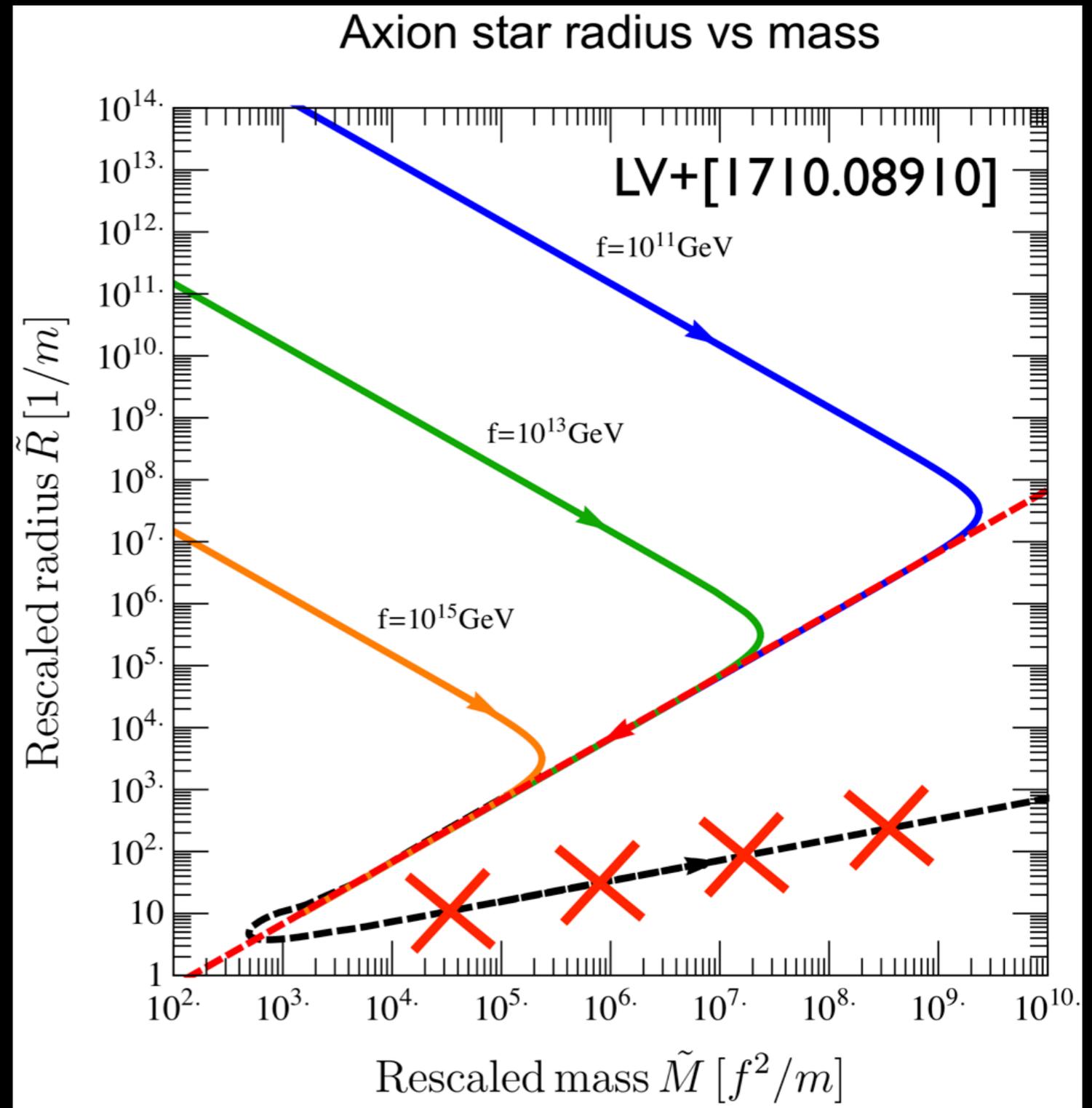
Relevant contributions:

- Kinetic pressure
- Gradient energy
- All orders in the potential

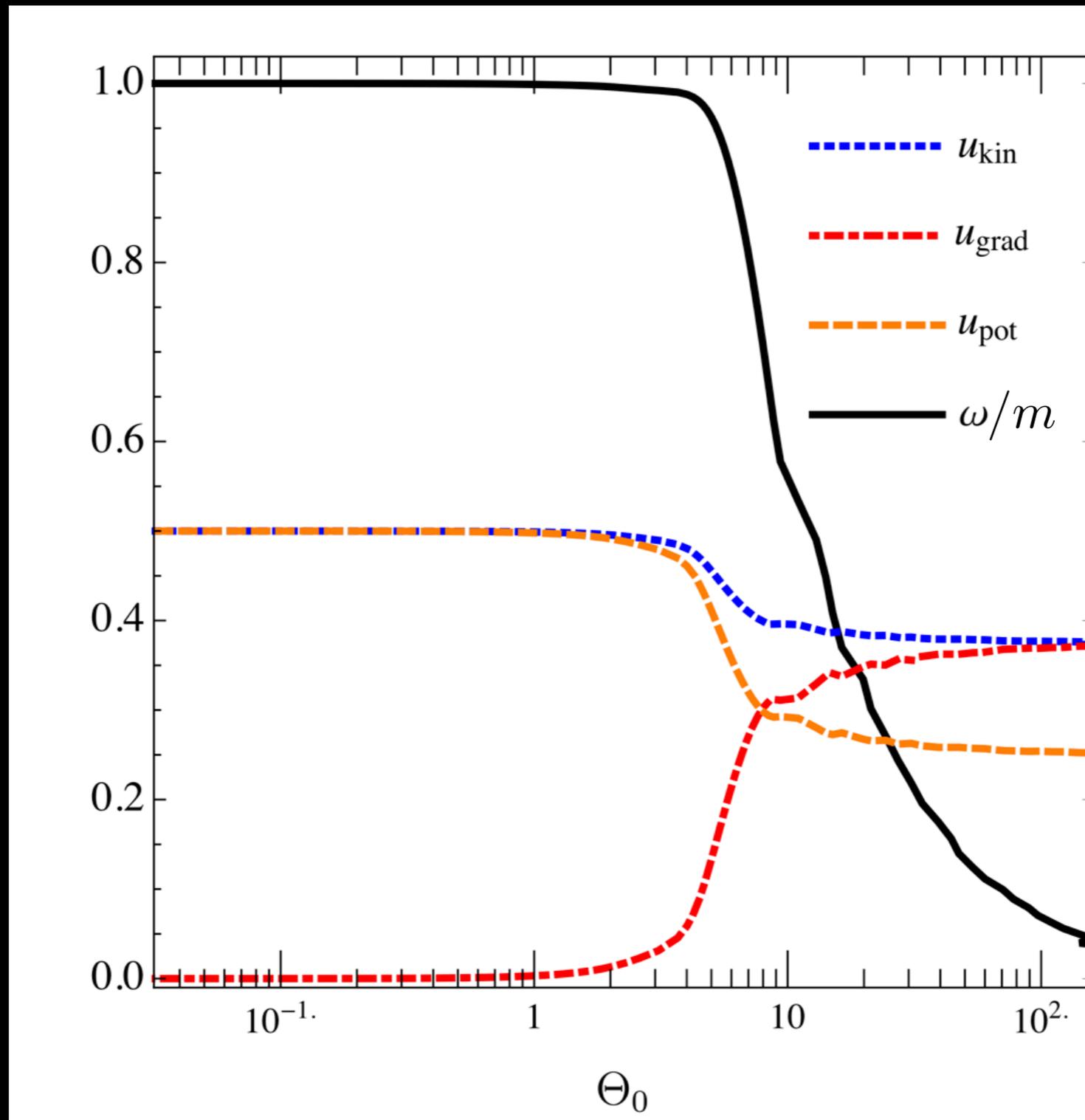
$$\rho \sim \Lambda^4 \quad \text{or} \quad R \propto M^{1/3}$$

Solutions are pseudo-oscillons of KGE with finite lifetime

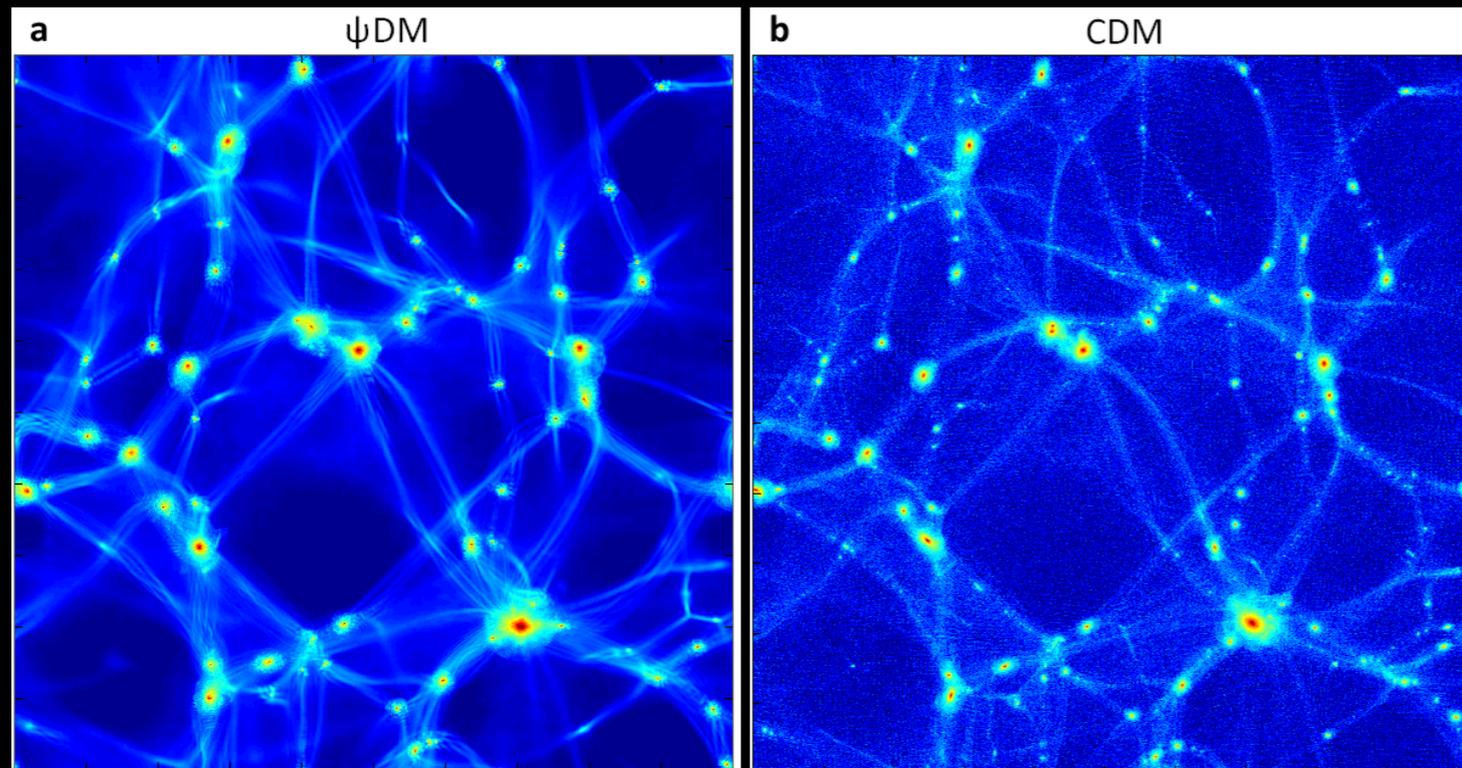
$$\tau_{\text{life}} = \mathcal{O} \left(\frac{10^3}{m} \right) \sim 10^{-7} \text{ s}$$



Transition from “critical” to “dense” branch

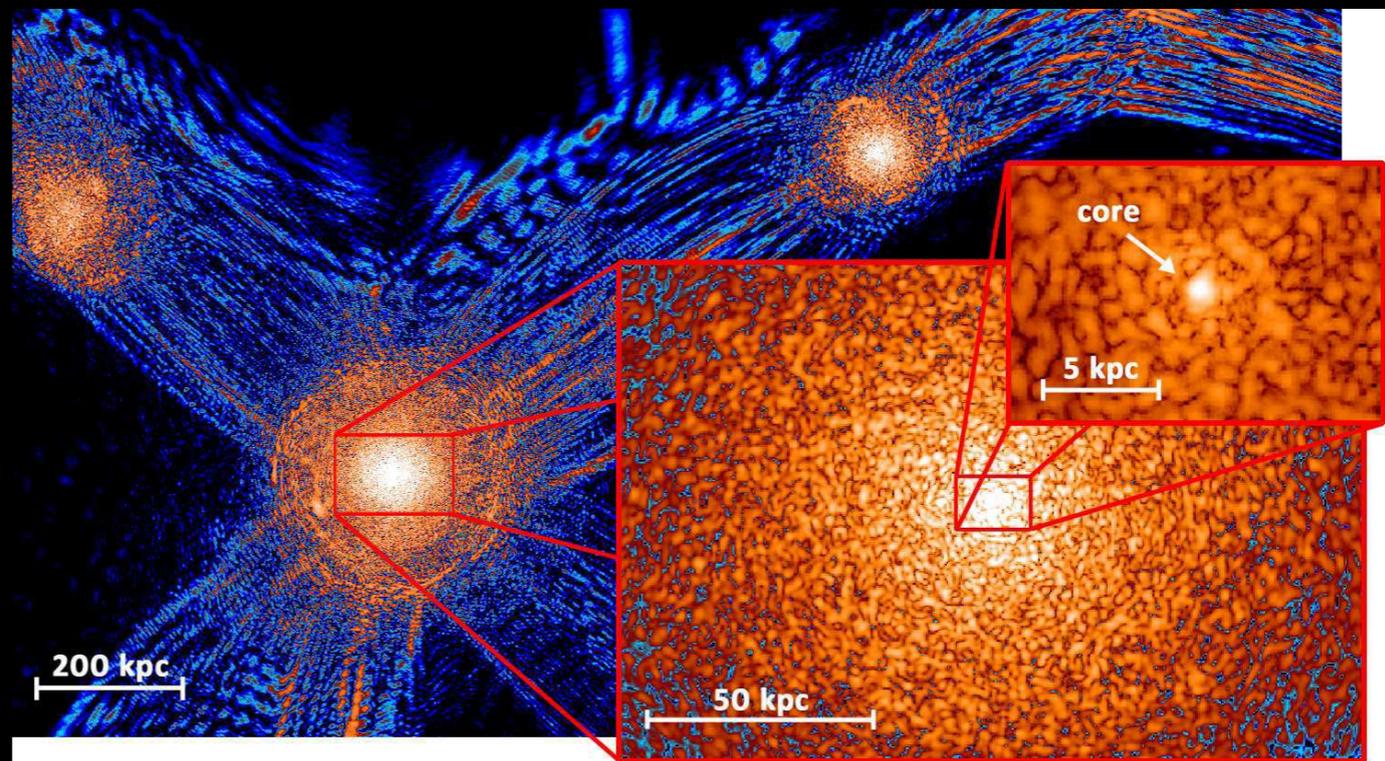


Soliton cores



Ultra-light axion DM
is indistinguishable
from CDM
on large scales....

... galactic-size
self-gravitating
soliton cores are
produced



Schive *et al.* Nature **10** 496 (2014)
Veeltman *et al.* PRD **98** 043509 (2018)

Conclusions

- It is an exciting period to work on dark matter compact objects!
- Details require much further efforts. Work in progress...
- Miniclusters and axion stars are possible laboratories!

